Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture

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Chapters 1 - 4

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CHAPTER 1

Introduction

Forestry and agricultural activities are widely recognized as potential greenhouse gas (GHG) mitigation options. Activities in forestry and agriculture can reduce and avoid the atmospheric buildup of the three most prevalent GHGs directly emitted by human actions: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CO_2 is the gaseous form of carbon bound with oxygen atoms.

The removal of atmospheric CO_2 through sequestration in carbon "sinks" is a mitigation option in forestry and agriculture that has received particular attention. Sequestration is the process of increasing the carbon content of a carbon pool other than the atmosphere (IPCC 2000). Terrestrial carbon pools include tree biomass (roughly 50 percent carbon), soils, and wood products. A carbon pool is a net sink if, over a certain time interval, more carbon is flowing into the pool than is flowing out of the pool. Likewise, a carbon pool can be a net source of CO_2 emissions if less carbon is flowing into the pool than is flowing out of the pool (IPCC 2000).

The forest and agriculture sectors can therefore act as either sources or sinks of CO_2 emissions. Agriculture (including croplands and livestock) is a particularly large source of CH_4 and N_2O emissions. Globally, land-use change, primarily tropical deforestation, accounts for approximately 20 percent of the world's annual, anthropogenic CO_2 emissions (IPCC 2000). An even greater amount of atmospheric CO_2 is removed by forests than is emitted by land-use change, such that the net global terrestrial sink (sink minus source) offsets approximately 11 percent of the world's CO_2 emissions due to fossil fuel combustion (IPCC 2000). Meanwhile, agriculture accounts for approximately 50 percent of global anthropogenic CH_4 emissions and 85 percent of global N_2O emissions (Scheehle and Kruger in press). CH_4 and N_2O are relatively potent greenhouse gases and can be placed on a comparable climatic basis with CO_2 through a Global Warming Potential (GWP) factor (see Box 1-1).

Box 1-1: Relative Global Warming Potential of Non-CO_2 Gases

The Global Warming Potential (GWP) compares the relative ability of each GHG to trap heat in the atmosphere over a certain time frame. Per IPCC (1996) guidelines, CO_2 is the reference gas and thus has a GWP of 1. Based on a time frame of 100 years, the GWP of CH_4 is 21, implying that a ton of methane is 21 times more potent than a ton of CO_2. The GWP for N_2O is 310. These values can be further transformed from CO_2 to carbon equivalent by dividing by 3.67, the mass ratio of CO_2 to C.

Note that GWPs from the *IPCC Third Assessment Report* (2001) are not used in this report because international GHG reporting guidelines are still based on the 1996 *IPCC Second Assessment Report*.

In the United States, forest and agricultural lands also comprise a net carbon sink. Removal of atmospheric CO_2 through sequestration is greater than CO_2 emissions through events such as forest harvests, land conversions or other uses, or fire. The U.S. carbon sink—over 90 percent of which occurs on forest lands—currently offsets 12 percent of U.S. GHG emissions from all sectors of the economy (EPA 2005; Figure 1-1). Agriculture accounts for about 30 percent of all CH_4 emissions and 72 percent of all N_2O emissions in the United States (op cit). Taken together, agricultural CH_4 and N_2O emissions are responsible for about 6 percent of all U.S. GHG emissions, expressed on a GWP-weighted CO_2 equivalent basis (op cit).

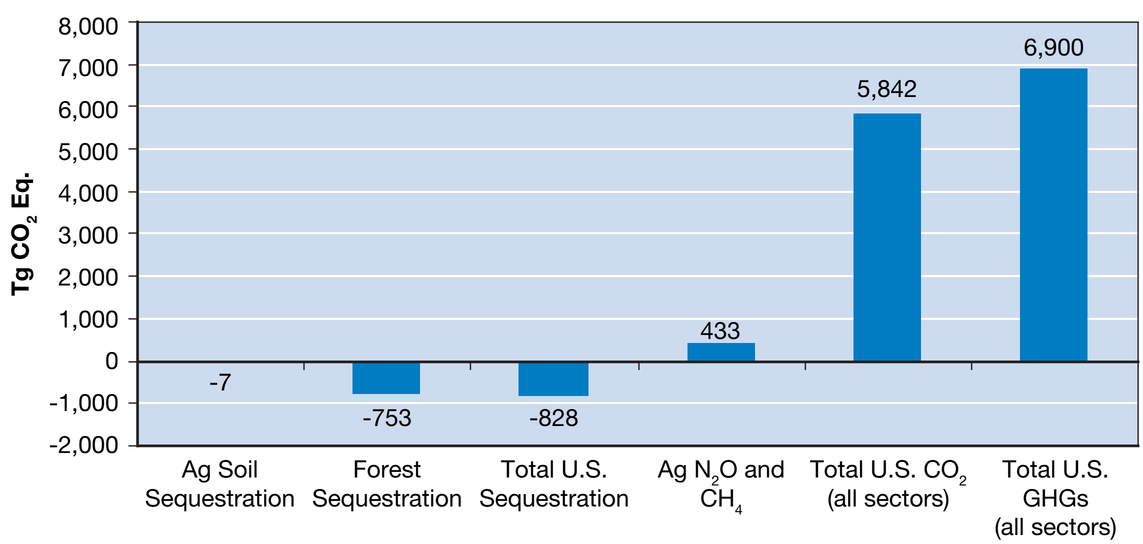
Key individual GHG mitigation options in U.S. forestry and agriculture include

- afforestation (tree planting);
- forest management, including silviculture, harvests, and forest preservation;
- agricultural soil carbon sequestration (primarily through changes in cropland tillage practices);
- fossil fuel use reduction associated with altered practices in agriculture;
- agricultural CH_4 and N_2O emission reduction (through a variety of modifications to livestock management and fertilizer applications); and
- biofuel offsets of fossil fuels (derived from bioenergy crops such as switchgrass).

These options generally fall into three categories (see IPCC [2001, 2000]): 1) options that avoid CO_2 emissions by preserving existing pools or sinks of carbon in tree biomass and soils (e.g., forest preservation), 2) options that enhance the removal of atmospheric CO_2 (sinks) through sequestration (e.g., afforestation), and 3) options that directly reduce fossil fuel-related CO_2 or CH_4 and N_2O emissions (e.g., biofuels and reduced fertilizer use). Chapter 2 discusses the individual mitigation options in greater detail.

Forestry and agricultural activities that either preserve or enhance carbon sinks exhibit unique and important features compared to mitigation options that directly reduce fossil fuel-related CO_2 or CH_4 and N_2O emissions. Two distinguishing characteristics are the saturation over time of carbon sequestration in vegetative biomass and soils, as a new equilibrium is reached for a given level of inputs, and the potential reversibility, or re-release, back to the atmosphere of sequestered carbon through natural or anthropogenic disturbances (e.g., tillage, or fire). The reversibility of

Figure 1 1: Forestry and Agriculture Net Contribution to GHG Emissions in the United States, 2003[a]



[a] Total agriculture and forestry sequestration also includes urban trees and landfilled yard trimmings and food scraps. Negative values represent a sink, positive values a source.

Source: EPA (2005).

carbon sequestration benefits is often referred to as the duration or permanence issue. Analyses presented in the report highlight the implications of saturation and reversibility of carbon sequestration in forestry and agriculture.

Purpose and Approach of this Report

This report aims to assess the GHG mitigation potential from forestry and agriculture in the United States over the next several decades, out to the 2050s, and in some cases beyond.

More specifically, the report aims to examine the following questions:

- What is the total GHG mitigation potential of the full suite of forestry and agricultural activities over time and at different costs?
- How does the portfolio of forestry and agricultural activities change over time and at different levels of GHG reduction incentives (or "GHG prices")?
- What is the regional distribution of GHG mitigation opportunities within the United States?
- How does the portfolio of activities, time profile, and regional distribution change across scenarios that reflect constant prices for GHG mitigation, rising prices, and fixed mitigation levels?
- What are the implications of carbon saturation and reversibility (or duration)?
- How do leakage and other implementation issues affect GHG mitigation benefits?
- What are some of the non-GHG environmental co-effects of GHG mitigation activities?
- What appear to be the top mitigation options, nationally and regionally, taking GHG, economic, implementation, and other environmental factors into account?

The analysis uses the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG) to examine these questions. FASOMGHG is a partial equilibrium economic model with comprehensive GHG accounting of the forest and agriculture sectors of the U.S. economy, linked to the rest of the world by international trade linkages. FASOMGHG can gauge the national aggregate response to GHG incentives (prices or GHG mitigation targets) and identify the most cost-effective mitigation opportunities at the national and regional levels. FASOMGHG can examine various scenarios with different approaches to achieving GHG mitigation (e.g., where all forestry and agricultural activities are included, where individual activities are included, or where all or individual GHGs are included).

All reported GHG mitigation activities in FASOMGHG occur as changes from a business-as-usual or baseline trajectory of carbon sequestration rates, GHG emissions, and economic activity in U.S. forestry and agriculture over time. Thus, *the mitigation results reported here are additional to projected baseline activity and GHG emission or sequestration levels*. FASOMGHG also reports some non-GHG environmental co-effects (such as changes in nonpoint loadings of nitrogen and phosphorous from agriculture) for a more complete analysis of mitigation outcomes.

Organization of Report

This report is organized as follows:

- **Chapter 2** describes the GHG mitigation options in U.S. forestry and agriculture represented in the FASOMGHG model, as well as some others not explicitly modeled for this report.
- **Chapter 3** presents the modeling framework of FASOMGHG and the model's projected baseline (with a brief comparison to other baseline studies), against which all mitigation estimates in subsequent chapters are reported.
- **Chapter 4** presents GHG mitigation results for the full suite of forestry and agricultural activities. Scenarios include a range of constant and rising GHG price incentives over time. Regional GHG mitigation results for these scenarios are presented as well.

- **Chapter 5** presents GHG mitigation results for the following selective scenarios: 1) three fixed GHG mitigation levels, 2) selection of individual or subsets of forestry and agricultural activities, and 3) addressing of CO_2 reductions only (versus all GHGs).
- **Chapter 6** evaluates some implications of taking activity-specific mitigation approaches and different payment methods. The chapter also presents estimates of the potential for "leakage," or the shifting of emissions to activities not subject to incentives.
- **Chapter 7** provides more detail on the non-GHG environmental co-effects of GHG mitigation activities.
- **Chapter 8** concludes the report by highlighting the report's key findings and the insights they hold for the realization of GHG mitigation potential in forestry and agriculture.

CHAPTER 2

Greenhouse Gas Mitigation Options in U.S. Forestry and Agriculture

Chapter 2 Summary

GHG mitigation opportunities in forestry and agriculture include afforestation (tree planting), forest management (e.g., altering harvest schedules or management inputs), forest preservation, agricultural soil tillage practices, grassland conversion, grazing management, riparian buffers, biofuel substitutes, fertilization management, and livestock and manure management. Each of these opportunities is described, with emphasis on their ability to avoid, sequester, and/or reduce CO_2, CH_4, and N_2O emissions. Sequestration activities can enhance and preserve carbon sinks and include afforestation, forest management, and agricultural soil tillage practices. Agricultural sources of CH_4, N_2O, and fossil fuel CO_2 can be reduced through changes in fertilizer applications and livestock and manure management. CO_2 emissions can be offset through biofuels, such as switchgrass and short-rotation tree species, which can be grown and used instead of fossil fuels to generate electricity.

This chapter also considers the unique time dynamics and accounting issues of carbon sequestration options: saturation (or equilibrium level) of carbon sequestration over time, potential reversibility of carbon benefits, and fate of carbon stored in products after forest harvests. In contrast, agricultural non-CO_2, fossil fuel CO_2, and biofuel options do not exhibit saturation or reversibility and are therefore generally considered permanent. Most mitigation opportunities described in this chapter are included in the analyses described in later chapters.

Forestry and agricultural activities can help reduce and avoid the atmospheric buildup of CO_2, CH_4, and N_2O in a number of ways. Atmospheric CO_2 can be removed and sequestered in tree biomass and soils, which can act as carbon sinks. Carbon stored in tree biomass and soils can be protected and preserved to avoid CO_2 releases to the atmosphere. Emissions of CO_2 can be avoided by reducing the use of energy-intensive inputs or by using biofuels, produced in the forest and agriculture sectors, instead of fossil fuels to produce energy. And agricultural CH_4 and N_2O emissions can be directly reduced by modifying livestock management and fertilizer applications. This chapter discusses the key forestry and agricultural mitigation options that either avoid, sequester, and/or reduce CO_2, CH_4, and N_2O. This chapter also discusses important issues related to the reversibility or permanence of forestry and agricultural options involving carbon sinks. The chapter presents the individual mitigation options as activities undertaken by landowners at the farm or forest-stand level. Subsequent chapters characterize the extent to which these mitigation options can be brought about by economic incentives operating at a nationally or regionally aggregated level. Examples of such incentives currently in place include government programs such as the Farm Bill, or voluntary GHG registries.

Carbon Sequestration

A number of practices within the forest and agriculture sectors can mitigate the atmospheric build-up of GHGs by removing CO_2 from the atmosphere and then storing it in forest and agroecosystems at a rate greater than its release back to the atmosphere through human and natural disturbances. These carbon sequestration activities can take on a variety of forms as discussed below.

Afforestation

Afforestation can be defined broadly as the establishment of trees on lands that were without trees for some period of time. Differing interpretations of this time period will dictate whether the establishment of forest cover is considered to represent afforestation or reforestation. The Intergovernmental Panel on Climate Change (IPCC) defines afforestation as the planting of new forests on lands that, historically, have not contained forests (IPCC 2000).

Reforestation often refers to the reestablishment of forest after a harvest in the United States. This report treats reforestation, or changes in the harvest–regeneration cycle, as part of "forest management," discussed below. FASOMGHG models afforestation separately, but reforestation is embedded within the broader activity of forest management in FASOMGHG and not treated separately.

Afforestation enhances carbon sequestration because land is allocated away from uses with relatively low carbon storage potential (e.g., conventional crop agriculture) to forest cover with higher carbon storage potential. Carbon accumulates in forest soils and biomass, the latter both below ground in the form of roots and above ground in stem, branches, and leaves. The rate of carbon accumulation for afforestation varies and depends on the newly planted tree species, climate, soil type, management, and other site-specific characteristics (e.g., 2.2 to 9.5 tonnes of CO_2 per acre per year, as reported by Birdsey [1996]; see Table 2-1). As a carbon sequestration activity, afforestation primarily affects atmospheric CO_2. The movement of land from agricultural use to forest also generally leads to a reduction in the various GHG emissions from agriculture, as described below. Most recent afforestation in the United States has occurred on pasturelands, where from 1982 to 1997 over 14 million acres were converted to forest cover (USDA NRCS 2000).

Forest Management

Forest management has traditionally focused on maximizing the value of harvested commercial timber over time. However, forests also can be managed to enhance carbon sequestration, via silvicultural practices or conservation of standing stocks. A managed forest will consist of one or several tree species in stands, and the mix can be designed so that the trees aid one another to ensure the fastest and most efficient biomass growth and thus higher sequestration potential. The landowner may choose to plant a moderately fast-growing species to accumulate timber (and carbon) faster; he or she may also use practices such as fertilization, controlled burning, and thinning to increase forest and carbon productivity.

Managed forests pass through multiple stand ages ranging from stand establishment to harvest. In a forest managed for timber production, the optimal harvest age is the time when the value of the additional timber growth obtained by delaying the harvest further is overtaken by the opportunity cost of the delay. Traditional forest rotation lengths vary by region and species type. The nonindustrial private forests (NIPF) of the southern United States are commonly managed with softwood or mixed species on a rotation of approximately 25 to 35 years or more. Rotations in commercial forestry, as practiced on forest industry-owned lands or very intensively managed NIPF lands, may be as short as half the length of the more typical NIPF rotation. The forest rotations of the western United States tend to be longer (between 45 and 60 years), because they consist of species that culminate growth at a later age. The varying rotation lengths allow for the production of multiple forest products including smaller-diameter pulpwood and larger-diameter sawtimber.

When carbon is considered a forest output, the value of delaying the rotation is higher because carbon accumulates as the trees grow (van Kooten, Binkley, and Delcourt 1995, Murray 2000). Thus, forest managers can enhance carbon sequestration

Table 2-1: Representative Carbon Sequestration Rates and Saturation Periods for Key Agriculture, Land-Use Change, and Forestry Practices

Activity	**Representative Carbon Sequestration Rate in U.S.** (Tonnes of CO_2 per acre per year, unless otherwise indicated)	**Time Over which Sequestration May Occur before Saturating** (Assuming no disturbance, harvest, or interruption of practice)	References
Afforestation[a]	2.2 – 9.5[b]	90 – 120+ years	Birdsey (1996)
Reforestation[c]	1.1 – 7.7[d]	90 – 120+ years	Birdsey (1996)
Avoided deforestation	83.7 – 172.1[e]	N.A.	U.S. Government (2000)
Changes in forest management	2.1 – 3.1[f]	If wood products included in accounting, saturation does not necessarily occur if carbon continuously flows into products	Row (1996)
Reduced tillage on croplands[g]	0.6 – 1.1	15 – 20 years	West and Post (2002)
	0.7[h]	25 – 50 years	Lal et al. (1998)
Changes in grazing management	0.07 – 1.9[i]	25 – 50 years	Follet et al. (2001)
Cropland conversion to grassland	0.9 – 1.9[j]	Not calculated	Eve et al. (2000)
Riparian buffers (nonforest)	0.4 – 1.0	Not calculated	Lal et al. (1998)
Biofuel substitutes for fossil fuels	4.8 – 5.5[k]	Saturation does not occur if fossil fuel emissions are continuously offset	Lal et al. (1998)

Note: Any associated changes in emissions of CH_4 and N_2O or—except for biofuels—fossil fuel CO_2 are not included.

[a] Values are for average management of forest after being established on previous croplands or pasture.

[b] Values calculated over 120-year period. Low value is for spruce-fir forest type in Lake States; high value for Douglas fir on Pacific Coast. Soil carbon accumulation included in estimate.

[c] Values are for average management of forest established after clearcut harvest.

[d] Values calculated over 120-year period. Low value is for Douglas fir in Rocky Mountains; high value for Douglas fir in Pacific Northwest. No accumulation in soil carbon is assumed.

[e] Values represent the assumed CO_2 loss avoided in a single year (not strictly comparable to annual estimates from other options). Low and high national annual average per acre estimates based on acres deforested from National Resource Inventory (NRI) data and carbon stock decline from the FORCARB model, from 1990 to 1997.

[f] Selected example calculated over 100 years. Low value represents change from unmanaged forest to plantations for pine-hardwood in the mid-South; high value is change from unmanaged forest to red pine plantations for aspen in the Lake States.

[g] Both West and Post and Lal et al. estimates here include only conversion from conventional to no till. Estimates do not include fluxes of other associated GHGs.

[h] Tillage rates vary, but this value represents a central estimate by Lal et al. for no-till, mulch till, and ridge till.

[i] Low-end estimate is for improved rangeland management; high-end estimate is for intensified grazing management on pastures, which includes the return of plant-derived carbon and nutrients to the soil as feces.

[j] Assumed that carbon sequestration rates are same as average rates estimated for lands under the USDA Conservation Reserve Program (CRP).

[k] Assumes growth of short-rotation woody crops and herbaceous energy crops, and an energy substitution factor of 0.65 to 0.75. Potential for changes in other GHG emissions not included.

by extending the harvest age of the managed forests. Over time, a new and higher carbon equilibrium will be reached. Carbon sequestration rates due to forest management practices vary depending on the practice itself, tree species, climate, topography, and soil type (e.g., 2.1 to 3.1 t CO_2/acre/year as reported by Row (1996); see Table 2-1).

When a forest is harvested, some carbon is immediately released to the atmosphere via the logging operation or milling process (about one-half or two-thirds is emitted at or near the time of harvest, depending on the product and region), but some is tied up in wood products for a number of years. Carbon from wood products may be released to the atmosphere many years in the future as the wood products decompose, the timing of which will depend on whether the products are short-lived (e.g., paper) or long-lived (e.g., housing lumber), and whether those products are discarded in landfills. The carbon sequestration and emissions that result from the harvest-regeneration cycle, including the wood products pool, are captured in the analyses presented later in the report.

Forest management primarily affects carbon pools and associated atmospheric CO_2, rather than fossil fuel CO_2 and non-CO_2 emissions. Although it uses equipment to establish, cultivate, and harvest stands of trees, forestry is less energy-intensive than agriculture because the management interventions are spread out episodically over time—a handful of interventions at most over 20 to 50 years for managed stands, less for stands that remain unmanaged. Therefore, there is limited ability to reduce energy-related CO_2 emissions in forestry. N_2O can be generated from forest fertilizer applications. However, relatively few forested acres receive fertilizer applications in a given year, so the aggregate effect of forestry on N_2O emissions is quite small.[1]

A form of forest management that can avoid CO_2 emissions is *forest preservation*, sometimes referred to as forest protection or a harvest set-aside. This entails adopting a management regime that does not involve harvesting. Although CO_2 emissions from harvesting may be avoided, the enhancement of carbon storage will cease when the forest meets its biophysical equilibrium—when carbon inputs equal carbon outputs. The carbon stock then essentially becomes a static pool.[2] Preservation of this form foregoes the option to replace a steady-state forest with a net-sequestering young forest. However, as shown in Harmon et al. (1990) after timber harvests in the Pacific Northwest, the on-site carbon declines significantly and it takes over 200 years for a newly reforested area to attain the storage capacity of an old growth forest.

The GHG benefits of *reducing or avoiding deforestation* in many ways simply mirror those from afforestation. However, there may be significant differences in the timing of GHG effects. Under afforestation, it takes decades for carbon to accumulate in forest soils and biomass. The process of deforestation—clearing forestland for another use —may release a substantial amount of carbon into the atmosphere rapidly upon the time of harvest. Although some carbon may be transferred off-site in the form of harvested wood products, a substantial portion is released immediately in harvesting and manufacturing (Skog and Nicholson 2000), on the order of, say, 150 to 800 t CO_2/acre.

The USDA's Natural Resources Inventory (NRI) shows that 5.7 percent of the private forested land base in the United States was deforested between the years 1982 and 1997 (USDA NRCS 2000), at an

[1] N_2O emissions associated with fertilization of forest soils are estimated to be 0.4 Tg CO_2 Eq. in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2003* (EPA 2005). These emissions are not included in the analyses presented in later chapters. According to EPA (2005), the rate of fertilizer application for the area of forests that receives fertilizer in any given year is relatively high. However, average annual applications are quite low (inferred by dividing all forestland by the amount of fertilizer added to forests in a given year).

[2] A mature forest, however, is not a static or unchanging carbon source; it is just that the net rate of sequestration is on average unchanging. But some studies suggest that even very old forested stands continue to sequester carbon (Lugo and Brown 1986, Phillips et al. 1998, Phillips et al. 2002a).

average annual rate of 241,147 acres per year. The primary conversion of forestland was to pasture and developed lands.

Avoiding or reducing deforestation does not necessarily imply that harvests will never occur. Rather, land can be retained in forested use and still be managed to produce timber through periodic harvesting. The process of eliminating harvests altogether is referred to as forest preservation or forest protection, as discussed above.

Agricultural Soil Carbon Sequestration

Croplands often emit CO_2 as a result of conventional tillage practices and other soil disturbances. Soils containing organic material that would otherwise be protected by vegetative cover are exposed through conventional tillage practices and become susceptible to decomposition. Frequent or intense tillage breaks down soil macroaggregates, thereby enhancing the exposure of carbon to microbial activity. This added soil exposure also enhances decomposition by raising the soil temperature (Lal et al. 1998). Adopting conservation tillage practices, changing the overall land and crop management, modifying cropping intensity, or retiring marginal lands from production can reduce or eliminate this exposure, thus reducing or eliminating the associated CO_2 emissions. Given widespread adoption of the management options discussed here, agricultural soils may be able to contribute more than a reduction in emissions; they have the potential to become a net sink of CO_2. These options are discussed briefly below.

In the United States, conservation tillage is typically defined as any tillage system that maintains at least 30 percent of ground covered by crop residue after planting (CTIC 1994). Conservation tillage eliminates one or several of the practices associated with conventional tillage, such as turning soils over with a moldboard plow and mixing soils with a disc plow (Lal et al. 1998). Conservation tillage practices, including no till, ridge till, and minimum till, allow crop residues to remain on the soil surface as protection against erosion.

Current estimates for CO_2 gains from conservation tillage range from about 0.6 to 1.1 t/CO_2/acre/yr, with differences in the estimated saturation period (West and Post 2002, Lal et al. 1998). A compilation of study results by West and Post (2002) suggests that soil carbon accumulation after adoption of conservation tillage typically occurs for periods of 15 to 20 years and then returns to a soil carbon steady state with no additional gains in carbon. Studies suggest that agricultural soils in the United States, on aggregate, have not reached a biophysical saturation point (IPCC 2000, Donigian et al. 1995, Kern and Johnson 1993). Further information on carbon saturation and reversal issues is provided below.

A final option aimed at reducing the potential decomposition of organic material is the retirement of economically marginal lands from production. Removing these lands from production can reduce CO_2 emissions, as well as N_2O emissions associated with fertilizer applications. Depending on the new land cover of these retired lands, they can become a carbon sink. Lands are often retired through federal programs such as the USDA Conservation Reserve Program (CRP).

Grassland Conversion

Grassland conversion refers to converting existing cropland to grasslands or pasture. Because there is continuous vegetative cover, the retention of soil carbon is higher than that for conventionally tilled cropland. Grassland conversion often involves cropland needing conservation treatments and may be part of a conservation program, such as CRP. Sequestration from this activity can vary from about 0.9 to 1.9 t CO_2/acre/yr (Eve et al. 2000, Table 2-1).

Grazing Management

While expanding grassland area can enhance carbon storage, further sequestration may be possible from improving the way grasslands are used for livestock grazing. Sequestration can be enhanced by increasing the quantity and quality of forages on pastures and native rangelands and by reducing carbon losses through the degradation process, thereby retaining higher soil carbon stocks (IPCC 2000). The range of mitigation estimates for grazing practices is wide, and the applicability of these numbers to the United States is a topic of ongoing research.

Grazing management practices can have multiple GHG effects. For instance, the quality of forage can affect livestock digestion processes and the amount of CH_4 that is emitted through enteric fermentation. Additionally, if nutrient inputs, in particular nitrogen-based fertilizers, are needed to enhance forage stocks, this can generate N_2O emissions post-application. The CH_4 and N_2O implications of livestock practices are addressed in more detail below.

Riparian Buffers

The establishment of riparian buffers can be viewed as a special case of either afforestation, forest management, or grassland conversion and thus fall under either forestry or agriculture. These practices are of particular interest because of their potential water quality co-benefits. Riparian buffers involve the establishment or maintenance of coarse vegetative land cover (trees, brush, grasses, or some mixture) on land near rivers, streams, and other water bodies. These actions are often focused around areas being cultivated or developed and used to filter the runoff of sediment, nutrients, chemicals, and other compounds that may impair water quality. Local, state, or federal government or private company guidelines often mandate that existing riparian buffers be left intact during timber harvests. Establishing or protecting these buffers can sequester CO_2 in the soil from the accumulation of organic material and in vegetative biomass if the buffer is planted or vegetation migrates into the area. This option also reduces baseline emissions from agriculture if the total cultivated area declines.

In 1997, a total of 199,600 acres of field borders and filter strips were in place on cropland, and a total of 1.6 million acres of grassed waterways existed (Uri 1997).

GHG Emissions Reduction Options in Agriculture

This section presents the agricultural mitigation options that can directly reduce CO_2, CH_4, and N_2O emissions, separate from the carbon sequestration options discussed above. CO_2 emission reduction options are discussed first; then the section addresses options to reduce non-CO_2 gases.

Reduction of CO_2 Emissions from Fossil Fuel Use

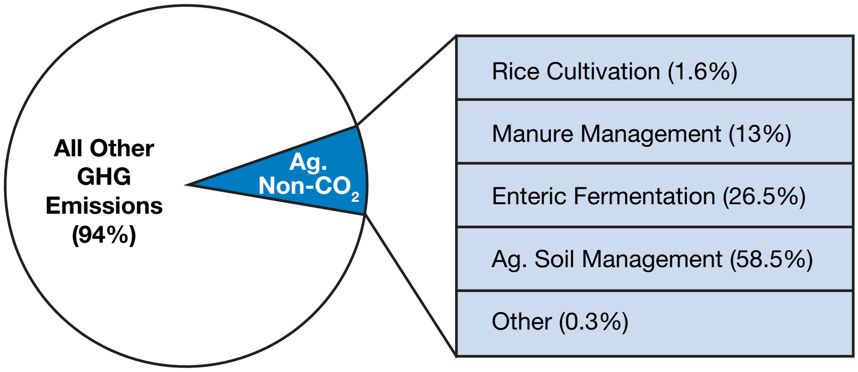
The main direct source of CO_2 emissions from U.S. agriculture is on-farm fuel use, although there are upstream releases related to the manufacture of equipment, fertilizer, and other agricultural inputs. Changes in practices that reduce the use of energy-intensive inputs can reduce CO_2 emissions from this sector. In the analysis presented in subsequent chapters, the CO_2 emissions captured because of agricultural management changes include emissions from direct use of fossil fuels in farm equipment, water pumping, and grain drying and fossil fuel use in fertilizer and pesticide production. For the purposes of this report, these emission reductions are associated with agricultural-sector activity, but other reports (e.g., annual EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks*) may consider these emissions associated with the energy or manufacturing sector.[3]

Reduction of Non-CO_2 GHG Emissions

Agriculture is a major source of non-CO_2 GHGs emissions, and the emissions can be reduced in numerous ways through changes in management practices. The GHGs of primary concern in the agriculture sector are N_2O and CH_4. These agricultural gases account for 433 Tg CO_2 Eq./year or over 6 percent of total U.S. GHG emissions (EPA 2005). Figure 2-1 displays the relative contribution of these activities and compares them to total U.S. GHG emissions. The relative potency of N_2O and CH_4 as climate change gases is greater than CO_2 on a per-unit basis (see Box 1-1 in Chapter 1).

[3] Please note that this report does not consider emissions from fossil fuel use in the forestry sector because of insufficient data on these emissions.

Figure 2 1: Agricultural Non CO_2 Emissions by Source Relative to All Other GHG Emissions



Source: EPA (2005).

N_2O emissions from agriculture account for just over 270 Tg CO_2 Eq./year or 63 percent of agricultural non-CO_2 emissions. Agricultural N_2O is largely tied to fertilizer application, nitrogen-fixing plants such as legumes, and manure emissions. Therefore, reductions can be accomplished by reducing nitrogen-based fertilizer applications, using nitrogen inhibitors, improving nitrogen nutrient management, altering crop mix, and reducing nitrogen content of animal feeds (McCarl and Schneider 2000). Economic incentives to reduce GHGs can alter the relative price of inputs and management practices that generate non-CO_2 emissions. The economic model used in this report accounts for these changes in prices (costs) and modifies practices and reduces emissions accordingly in the analyses that follow.

CH_4 emissions account for 161.4 Tg CO_2 Eq. per year or 37 percent of agricultural non-CO_2 emissions and are due in large part to emissions from livestock manure and enteric fermentation in the digestive tracts of ruminant livestock (see Table 2-2). Changes in feeding ratios and manure management strategies can be undertaken to reduce these emissions. Rice cultivation is also a source of CH_4 emissions, although less so in the United States than in other parts of the world. CH_4 uptake and emissions from cropland soils are not well understood and are not included in the EPA GHG inventory reports or in this analysis. The following sections outline four major sources of agricultural non-CO_2 emissions and potential mitigation options.

Table 2-2: Agricultural Non-CO_2 Emissions by Source, 2003 (Tg CO_2 Eq.)

Emission Source	CH_4	N_2O	Total Non-CO_2
Agricultural soil management	—	253.5	253.5
Enteric fermentation	115.0	—	115.0
Manure management	39.1	17.5	56.6
Rice cultivation	6.9	—	6.9
Field burning of agricultural residues	0.8	0.4	1.2
Total emissions from agriculture	161.8	271.5	433.2

Source: EPA (2005).

Agricultural Soil and Fertilization Management

N_2O emissions are produced in soils through the processes of nitrification (aerobic microbial oxidation of ammonium [NH_4] to nitrate [NO_3]) and denitrification (anaerobic microbial reduction of nitrate to di-nitrogen [N_2]). Agricultural soil N_2O emissions represent 58 percent (253.5 Tg CO_2 Eq.) of agricultural non-CO_2 emissions (Table 2-2). The application of nitrogen-based fertilizers to croplands is a key determinant of N_2O emissions, because excess nitrogen not used by the plants is subject to gaseous emissions, as well as leaching and runoff. A viable mitigation option to reduce soil N_2O emissions is to adopt management practices that ensure the most efficient use and application of nitrogen-based fertilizer while maintaining crop yields.

Enteric Fermentation

The primary source of CH_4 emissions, which represents 27 percent (115.0 Tg CO_2 Eq.) of agricultural non-CO_2 emissions (Table 2-2), is ruminant livestock and the microbial fermentation process of feed in their digestive system (rumen). The amount of CH_4 emitted from an animal depends primarily on the efficiency of the animal's digestive system, which is determined by the animal's feed or diet.

Viable options are available for reducing CH_4 emissions from enteric fermentation, because CH_4 releases essentially represent wasted energy that could otherwise be used to produce milk or beef. Direct approaches attempt to increase the rumen efficiency, thus reducing the amount of CH_4 produced per unit of feed. Indirect options focus on increasing animal productivity, reducing the amount of CH_4 emitted per unit of product (e.g., milk, beef). These direct and indirect approaches include options for improving the feed-intake efficiency (e.g., use of bovine somatotropin [bST]), altering livestock management practices (e.g., elimination of stocker phase in beef production), and using intensive grazing.

Manure Management

Livestock manure can produce both CH_4 and N_2O emissions. The level of CH_4 emissions depends on the way the manure is handled and stored. In many livestock operations in the United States, animals are raised in confined areas, and their manure is diverted to holding areas for further management. CH_4 is produced by the anaerobic decomposition of manure that is stored in lagoons, ponds, pits, or tanks. N_2O is produced through the nitrification and denitrification of the organic nitrogen in livestock manure and urine. The combined CH_4 and N_2O emissions from livestock manure represent 13 percent (56.6 Tg CO_2 Eq.) of agricultural non-CO_2 emissions (Table 2-2).

Anaerobic digesters that cover and capture the CH_4 emitted from collected manure, and potentially used as an on-farm energy source, represent a key mitigation option. The specific storage system will determine the type of digester or digestion process that will be applied to the manure (e.g., plug and flow, unheated or heated lagoon, complete mix). The emitted gas can either be converted into electricity for use as an on-farm energy source or consumed through flaring the collected gas. In either case, CH_4 is mitigated and CO_2 is released, but this option still remains a viable option for net GHG reductions because the GWP for CH_4 is 21 times higher than CO_2. Another CH_4 mitigation option allows for aerobic decomposition of manure as a solid on pasture-, range-, or paddock lands.

Rice Cultivation

Rice production under flooded conditions results in CH_4 emissions through the anaerobic decomposition of organic matter in the fields. Approximately 90 percent of the world's harvested rice area is grown under this management practice for some period of time (Wassman et al. 2000). In the United States, all rice is cultivated under flooded conditions (EPA 2005), but rice CH_4 accounts for less than 2 percent (6.9 Tg CO_2 Eq.) of U.S. agricultural non-CO_2 emissions (Table 2-2). Mitigation options for rice CH_4 include changes in water management regime, the use of inorganic fertilizers, and different cultivar selection. In the analyses presented later in the report, rice CH_4 is reduced through decreases in rice acreage.

Biofuel Offsets of Fossil Fuels

Products from the forest and agriculture sectors can mitigate GHGs by serving as substitutes for fossil fuels or for products that depend on fossil fuel combustion in their production. Though these options do involve forest and agricultural carbon sinks, the primary GHG benefits of these options can generally be treated as equivalent to permanent emission reductions.

A potential process for reducing atmospheric CO_2 is the cultivation of perennial grasses, short-rotation woody crops, or traditional crops for biofuel production. The production of these alternative energy sources created from biomass has the potential to reduce the use of fossil fuels used in the power generation and transportation sectors, the largest sources of CO_2 emissions in the United States.

The essential premise of biofuel as a means to reduce GHGs is based on their renewability. Biofuels, like fossil fuels, release GHGs when burned for energy production. However, biofuels are releasing GHGs (CO_2) that have been removed from the atmosphere through photosynthesis and stored in biomass. In essence, the plants are harvesting GHGs for use in energy production. In a steady state of biofuel production and use, there is little to no net addition to atmospheric GHG concentrations. However, fossil fuel combustion transfers carbon to the atmosphere that was stored underground in coal, petroleum, or natural gas reserves without replacing the fossil carbon stock and thereby, on net, raises GHG concentrations.

Specific examples of biofuel options include using forestry and agricultural residues and planting dedicated energy crops such as switchgrass or poplar to use as feedstock for electric power generation. In 2002, biomass accounted for only 1 percent (37 billion kilowatt hours) of U.S. electricity generation and is projected under baseline conditions to remain at 1.3 percent of generation (81 billion kilowatt hours) by 2025 (Energy Information Administration [EIA] 2004). In analyses presented later in this report, emission reductions due to biofuels used in power generation result from comparing net GHG emissions of coal-fired plants to net GHG emissions of biomass-fired plants. Using biofuels as a supplement to coal in co-fired plants is also possible. Finally, corn can be grown to produce ethanol as replacement for liquid fossil fuels (though this latter option generates little GHG mitigation in this report's analysis).

Unique Time Dynamics of Carbon Sequestration Options

Forestry and agriculture practices that preserve and enhance carbon storage in soils and biomass exhibit unique and important features compared to mitigation activities in all sectors of the economy that reduce fossil fuel CO_2, CH_4, N_2O, and emissions of other GHGs. The primary distinguishing characteristics are mainly related to the unique temporal dynamics of sequestration options.

Comprehensive GHG accounting of sequestration options requires the inclusion of both sequestration and release of CO_2 and sometimes CH_4 and N_2O. This tracking needs to occur over long timeframes both during normal land-use and management practices and in mitigation activities. Three fundamental factors need to be considered: the slowdown or so-called *saturation* (or approach to equilibrium) of sequestration rates, the potential for *reversal* of carbon benefits if sequestered carbon is re-released into the atmosphere at some future point in time, and the fate of carbon in long-lived products after the time of harvest. These issues of carbon permanence are addressed briefly below and more thoroughly again in Chapter 6.

"Saturation" of Carbon Sequestration to Equilibrium

The amount of carbon that can be sequestered in agricultural soils and forest ecosystems is ultimately constrained by biophysical factors. Once a sequestration activity such as afforestation or crop tillage change takes place, the rate of the ecosystem's carbon inputs exceeds the rate of its carbon outputs, thereby leading to a net accumulation of carbon stocks on-site. However, the biophysical processes evolve over time until the rate of carbon output just equals the rate of carbon inputs. At that point, the system has reached a new carbon equilibrium, and no net carbon stock accumulations can be expected beyond that point. In broad discussions of carbon sequestration strategies, this process is typically referred to as carbon "saturation."[4]

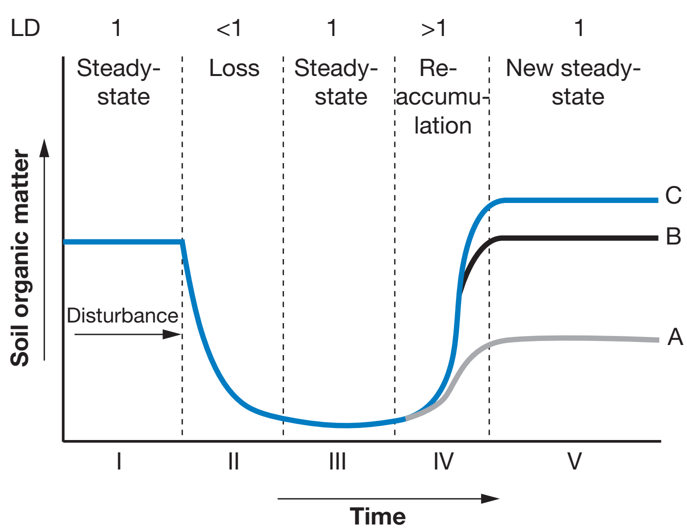
The time it takes to reach this steady state varies across soil types, site conditions, and management practices. A key determinant of saturation time is the land-use history of a given parcel—when anthropogenic and natural disturbances occurred, what land-use practices were involved, and how long they persisted. If soils in the northern Corn Belt, for example, were first tilled from native grasslands with a given soil organic matter (SOM) content in the early 20th century, cropped using conventional tillage practices, and then converted to lower-tillage practices, this land-use history will strongly influence the level of SOM in the soils today. Further, alternative management of these soils to enhance SOM levels will be limited by the difference between the current SOM level and the potential or original level (see Figure 2-2).

Studies of soil conservation tillage effects on carbon sequestration range from relatively quick adjustment to steady state (e.g., 15 to 20 years [West and Post 2002] to longer saturation periods in excess of 50 years [Lal et al. 1998]; see Table 2-1). The West and Post (2002) analysis reviews studies of SOM changes from tillage and concludes that, in most cases, saturation is reached at about 15 years, with some residual carbon uptake after that period.

Figure 2-3 summarizes their analysis. Based on their work, the analyses presented later in this report use a soil saturation assumption of 15 years.

Forest carbon sequestration tends to saturate over longer periods of time, 80 years or more after stand establishment in the United States, varying by

Figure 2 2: Conceptual Model of Soil Organic Matter Decomposition and Accumulation Following Disturbance

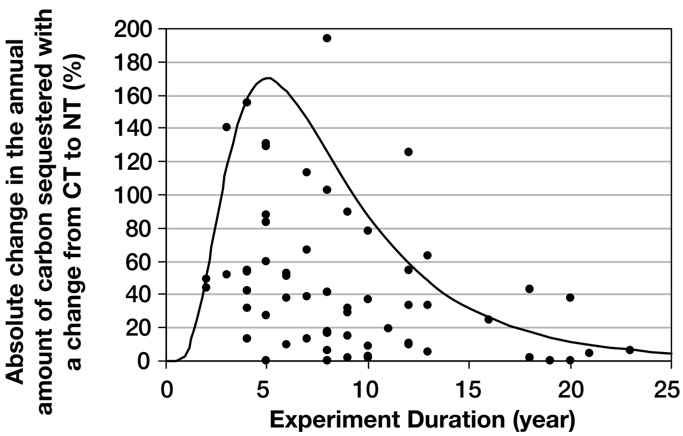


Note: At steady state (II), carbon (C) inputs from litter (L) equal C losses via decomposition (D) (i.e., L/D = 1). After a disturbance, D often exceeds L, resulting in loss of C (II), until a new, lower steady state is reached (III). Adoption of new management, where L exceeds D results in a reaccumulation of C (IV) until a new, higher steady state is reached (V). The eventual steady state (A, B, or C) depends on the new management adopted.

Source: Figure 4-5 in Kauppi and Sedjo (2001), drawn from work of Johnson (1995) and IPCC (2000).

[4] It is necessary to make a scientific distinction between saturation, which refers to the ultimate biophysical limits to growth of an ecosystem, and equilibrium, which refers to a system in steady state where inputs equal outputs. The latter is a subset of the former. In other words, some systems can be in equilibrium, but not be at their biophysical saturation point, but if a system is at its saturation point, it is also in equilibrium. By and large, our discussion of sequestration dynamics refers to the time it takes for a system to reach its new equilibrium point after a land-use or land management change. In some cases, this new equilibrium will not reflect the ultimate biophysical saturation point. However, to maintain consistency with typical word choice, we use the term "saturation" to reflect the broad process of reaching a new equilibrium. For further discussion on the issue of soil carbon saturation, see West and Six (2005).

Figure 2 3: Absolute Change in the Annual Rate of Carbon Sequestered Following a Change from Conventional Tillage (CT) to No Till (NT)



Note: Estimates are relative to soil carbon values under CT over the experiment duration, which means the estimated change in annual sequestration is greater if carbon under CT is declining while carbon under NT is increasing. Values in the figure are absolute (no negative values) and represent the percentage change in the estimated annual sequestration rate, not the percentage change in soil carbon. The method for calculating this value is outlined by West and Post (2002). A nonlinear regression curve has been fitted to the data, as described by West et al. (2004), to indicate the estimated peak and duration of soil carbon sequestration. This estimate represents the potential to sequester carbon, and soils or environments that have limiting factors that decrease or inhibit soil carbon sequestration are represented by values below the curve. Values considered as statistical outliers are not shown in the figure.

Source: West and Post (2002).

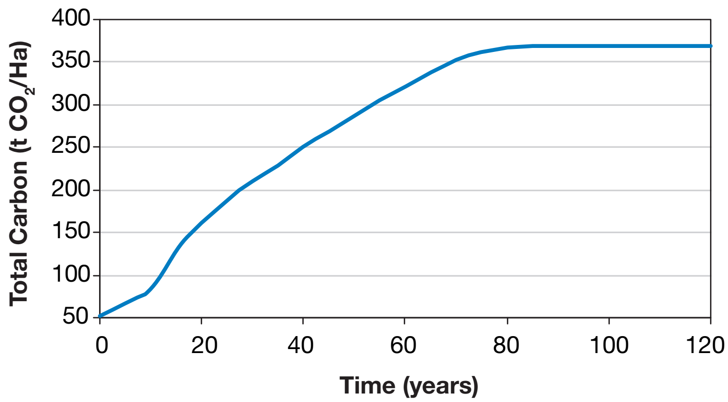
forest type and site class (Birdsey 1996). Figure 2-4 illustrates a typical carbon growth pattern following conversion of agricultural lands to a pine plantation in the U.S. South. However, research has shown that old growth forests in the United States (e.g., Douglas fir or redwood stands in the Pacific Northwest Westside [Harmon et al. 1990] and in the tropics) may continue to accumulate carbon for hundreds of years, although at a decreased rate (Lugo and Brown 1986, Phillips et al. 1998, Phillips et al. 2002a, 2002b).

Saturation has important implications for assessing forestry and agricultural sequestration in the United States, as saturation rates vary across carbon pools, activities and land conditions. In the long run, though, the rate at which activities accumulate carbon at certain periods of time is not as critical to climate change mitigation as the maximum, cumulative carbon storage potential of the alternative land use. Saturation is a dynamic phenomenon as well and may respond to climate and/or future environmental and technological change.

Reversibility of Carbon Sequestration

The accumulated carbon from forestry and agricultural sequestration practices can be re-released back to the atmosphere through either natural or

Figure 2 4: Carbon Accumulation on an Afforested Stand to Saturation



Notes: 1) Saturation reached in about year 80, and no additional carbon sequestration afterward. 2) Soils contain 50 t CO_2 of soil organic matter in year 0.

Source: Birdsey (1996).

intentional disturbances, such as fires, management changes, or logging. The climate benefits of carbon sequestration activities are therefore potentially reversible. This is sometimes referred to as the permanence or duration issue. Note that even if incentives for carbon sequestration, such as those evaluated later in this report, cause harvests to be delayed, harvesting may still occur eventually unless expressly prohibited by the incentive program or policy.

Designing approaches for carbon sequestration activities that appropriately capture the property rights for the sequestered carbon and the liabilities for carbon reversal remains a challenge. These issues are examined further as part of the discussions of Chapter 6.

Accounting for Carbon after Timber Harvests

When timber is harvested, some of the carbon that has accumulated over the years is removed from the site and the rest is left on-site to decay over time. The carbon that is removed from the site will at any time following the harvest be in one of the following carbon pools:

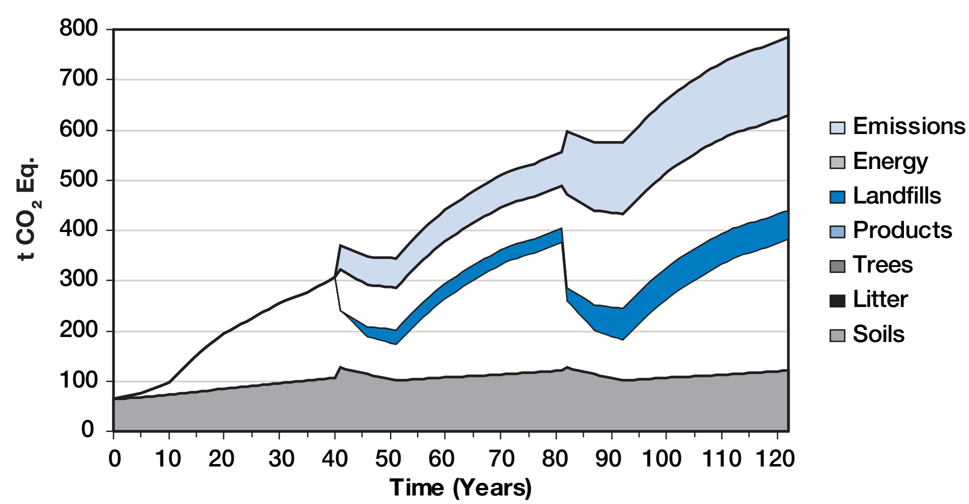
- products in use (very short-lived for paper, quite long for lumber);
- landfilled, often stored for extended periods; or
- atmosphere through combustion (sometimes to produce energy) or product decay.

Figure 2-5 illustrates the carbon flows over time under rotational forestry. In addition to the carbon fate after harvest discussed above, the figure shows the reaccumulation of forest carbon in on-site pools (trees, litter, soil) as a result of planting trees after each harvest. The figure illustrates that rotation forestry can continue to sequester carbon over extended periods of time through the continued accumulation of carbon stored in products and landfills. A complete accounting system should capture all of these product flows.

Addressing Carbon Sequestration Dynamics in this Report

In analyses presented later in this report, the dynamics of saturation, reversibility, and post-harvest destination of sequestered carbon are handled within the framework of the FASOMGHG model. As described in detail in Chapter 3, this model comprehensively accounts for both carbon sequestration and losses (i.e., sinks and sources) in forestry and agriculture over time, including harvested product pools. The accounting of both carbon sinks and sources occurs in the baseline and mitigation scenarios. Specific arrangements for addressing reversibility risk are discussed in Chapter 6.

Figure 2 5: Cumulative Carbon Changes for a Scenario Involving Afforestation and Harvest



Data Source: Birdsey (1996).

CHAPTER 3

Modeling Framework and Baseline

Chapter 3 Summary

The FASOMGHG model is used to evaluate the joint economic and biophysical effects of GHG mitigation scenarios in U.S. forestry and agriculture. This model includes all major GHG mitigation options in U.S. forestry and agriculture and accounts for changes in CO_2, CH_4, and N_2O, including carbon sequestration and emissions over time. The model also generates estimates of nutrient loadings and soil erosion in agriculture. FASOMGHG covers private timberlands and all agricultural activity across the conterminous ("lower 48") United States, broken into 11 regions, and tracks five forest product categories and more than 2,000 production possibilities for field crops, livestock, and biofuels. FASOMGHG runs simulations for 100-year periods and reports results on a decadal basis. The model simulates the actions of producers and consumers with perfect foresight of future demands, yields, technologies, and GHG prices.

Mitigation analyses presented later in this report pivot off a FASOMGHG baseline (business as usual) projection of future economic and GHG effects. This baseline estimates that private forests will constitute a net carbon sink for several decades, though the sink is projected to diminish over time. Direct (including N_2O and CH_4) and indirect sources and sinks in the forest and agriculture sectors constitute a net emission source in the baseline of 270 Tg CO_2 per year in the 2010 decade. This net baseline emission rate nearly doubles by around 2030 and then stabilizes somewhat thereafter. This pattern is largely dictated by carbon sink dynamics.

This chapter first presents the modeling framework and data employed by the FASOMGHG model of the U.S. forest and agriculture sectors, which is the analytical foundation for this report. After describing model details, the chapter moves to the FASOMGHG business-as-usual (BAU) baseline, focusing on future projections of GHG emissions and sequestration in the U.S. forest and agriculture sectors. The FASOMGHG baseline is evaluated against recent trends in land use, GHG emissions and sequestration, and baseline projections developed by other recent studies.

Modeling Framework

Examining the dynamic role of forest and agricultural GHG mitigation requires an analytical framework that can depict the time path and GHG consequences of forestry and agricultural activity. To credibly model or simulate baseline and additional mitigation effects in these sectors, it is critical to have as complete coverage as possible along several key dimensions:

Sectoral

- Sufficient detail to identify targeted economic opportunities within and across the sectors (e.g., land-use change, forest management, agricultural management, biofuel production).

- Inclusion of market-clearing processes and resource competition needed to show the commodity market (forest and agricultural products) feedback effects of mitigating GHGs in forestry and agriculture.

Spatial

- Heterogeneity of biophysical and economic conditions within and across regions as it relates to the production of food, fiber, fuel, and the GHG consequences thereof. For instance, regional carbon sequestration rates can vary spatially by more than an order of magnitude.
- Competition for region-specific resources, such as land and water, which affects economic responsiveness in forestry and agriculture to traditional commodity market signals and to GHG economic incentives.

Temporal

- Ability to capture dynamic biophysical processes (e.g., soil and biomass carbon accumulation over time, fate of harvested wood products).
- Ability to capture dynamic economic processes (investment, technological progress, demand trends, traditional commodity, and GHG market developments).

In addition, models used for policy evaluation should, to the extent possible, be calibrated to and validated by observed economic and biophysical phenomena. FASOMGHG encompasses the dimensions just defined and thereby provides an analytical foundation to address the issues raised in this report. This section of the report describes FASOMGHG's conceptual framework, scope of coverage, data, and other details.

General Model Description

FASOMGHG is an augmented version of the Forest and Agricultural Sector Optimization Model (FASOM) (Adams et al. 1996) as developed by Lee (2002). The model has all of the forest- and agriculture-sector economic coverage of the original FASOM model unified with a detailed representation of the possible mitigation strategies in the agriculture sector adapted from Schneider (2000) and McCarl and Schneider (2001).

FASOMGHG is a 100-year intertemporal, price-endogenous, mathematical programming model depicting land transfers and other resource allocations between and within the forest and agriculture sectors in the United States. The model solution portrays a multiperiod equilibrium on a decadal basis. The results from FASOMGHG yield a dynamic simulation of prices, production, management, consumption, and GHG effects within these two sectors under the scenario depicted in the model data.

FASOMGHG can simulate responses in the U.S. forest and agriculture sectors to economic incentives such as GHG prices or mitigation quantity targets. Economic responses include changes in land use between and within the sectors and intrasectoral changes in forest and agricultural management.

FASOMGHG's key endogenous variables include

- land use;
- management strategy adoption;
- resource use;
- commodity and factor prices;
- production and export and import quantities; and
- environmental impact indicators:
    - — GHG emission/absorption (CO_2, CH_4, N_2O) and
    - — surface, subsurface, and groundwater pollution for nitrogen, phosphorous, and soil erosion.

Table 3-1 summarizes FASOMGHG's key dimensions. The remainder of the section provides more detail on the model's structure, data, and key parameters.[1]

[1] For more complete model detail on FASOMGHG and its affiliated models, consult Dr. Bruce McCarl's Web site, (http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers.htm).

Table 3-1: FASOMGHG Model: Key Dimensions

Model Dimension	Forest Sector	Agriculture Sector
General scope and coverage		
Geographic coverage	Land coverage for conterminous United States with other regions linked by international trade	Same
Regional detail	11 U.S. regions, 9 of which produce forest goods	11 U.S. regions, 10 of which produce agricultural goods
Land ownership coverage	All private timberland in conterminous United States	All agricultural land in major commodity production in the conterminous United States
Economic dimensions		
Economic modeling approach	Optimizing producer and consumer behavior over finite time horizon	Same
Time horizon	Model base year = 2000 Resolution = 10-year time steps Typically run for 100 years	Same
Discount rate	4%	Same
Commodities	10 commodities 5 products: sawlogs, pulpwood, fuelwood and milling residues (2) 2 species: softwood and hardwood	48 primary products 45 secondary products
Price and cost data	Resource Planning Act (RPA) assessment (USDA Forest Service 2003)	USDA NRCS data with updates based on *Agricultural Statistics*
Supply/land inventory	USDA Forest Service Forest Inventory and Analysis Data	USDA NRI, Agricultural Census, and NASS data
Supply/biophysical yield	USDA Forest Service ATLAS model (Mills and Kincaid 1992)	Crop budgets and EPIC (Williams et al. 1989) model simulations
Demand	Adapted from demand models used in latest RPA Assessment (USDA Forest Service 2003)	Variety of demand studies (see "Agricultural Product Demand" on page 3-9)
International trade	10 excess-demand regions facing each timber-producing region plus Canada	28 international regions for the main traded commodities plus excess supply and demand for others
Environmental variables		
GHG coverage	CO_2 as carbon sequestration in forest ecosystem pools and in harvested wood products	CO_2 sequestration and emissions CH_4 emissions N_2O emissions
Non-GHG environmental indicators	Timberland area by region, species, owner, age class	Agricultural land allocation Tillage practices Irrigation water use
	Forest management intensity	Cropland loadings of nitrogen, phosphorous, potassium, erosion, and pesticides

Geographic Coverage/Regional Detail

FASOMGHG covers forest and agricultural activity across the conterminous ("lower 48") United States, broken into 11 separate regions (see Table 3-2 and Figure 3-1).

The 11 regions are a consolidation of regional definitions that would otherwise differ if the forest and agriculture sectors were treated separately. The forest sector considers nine major production regions and agriculture distinguishes 10 regions.[2] The 11-region breakdown reflects the existence of regions for which there is agricultural activity but no forestry, and vice versa. For instance, the Northern Plains (NP) and Southwest (SW) regions reflect important differences in agricultural characteristics, but no forestry activity is included in either region. Likewise, there are important differences in the two Pacific Northwest regions (PNWW, PNWE) for forestry, but only the PNWE region is considered a significant producer of the agricultural commodities tracked in the model.

Land Base

FASOMGHG covers all cropland and pastureland in production throughout the conterminous United States. Livestock grazing is also tied to the use of animal unit months (AUMs) on public rangelands, largely in the western states. The model accounts for timber production from all U.S. forestlands, private and public, and timber imports. However, the forest-sector mitigation activities and GHG (carbon) accounting are limited to private timberland in the conterminous United States. Mitigation and carbon flows from public timberland and all forestlands too unproductive to be considered timberland are excluded from the model because of data limitations and because model development has heretofore focused on potential mitigation responses of the private sector to market-based incentives.[3] The potential impact of excluding public lands from the forest-sector analysis is addressed further below.

General Economic Concepts: Optimizing Behavior

At its heart, FASOMGHG solves a constrained dynamic optimization problem defined as follows:

Objective Function: Maximize the net present value (NPV) of the sum of producer and consumer surpluses across the forest and agriculture sectors over time (100 yrs), including any GHG payments introduced by a mitigation scenario.

Constraints:

- Total production = total consumption
- Technical input/output relationships hold
- Land-use balances

By maximizing the sum of producer and consumer surplus, the model ensures that all suppliers and demanders are making optimal choices about what to produce and consume. Because these choices occur over time, the optimizing nature of the model assumes that producers and consumers have *perfect foresight* regarding future demands, yields, technologies, and prices. See Box 3-1.

Given that the model is defined for a finite period, there will be immature trees of some age at the end. If the model did not place a value on these forests, the optimizing nature of the model would be inclined to deplete all timber at the end of the projection period rather than leave it around for future harvests. Similarly, agricultural land values at the end of the period must also be considered to ensure that land is not inappropriately converted as a result of a perceived lack of opportunity cost. To counter these ending-period anomalies, *terminal conditions* are imposed on the model that value ending immature trees and land remaining in agriculture. FASOMGHG assumes that forest management is, from the last period onward, a continuous or constant flow process with a forest inventory that is "fully regulated" on rotations equivalent to those observed in the last decades

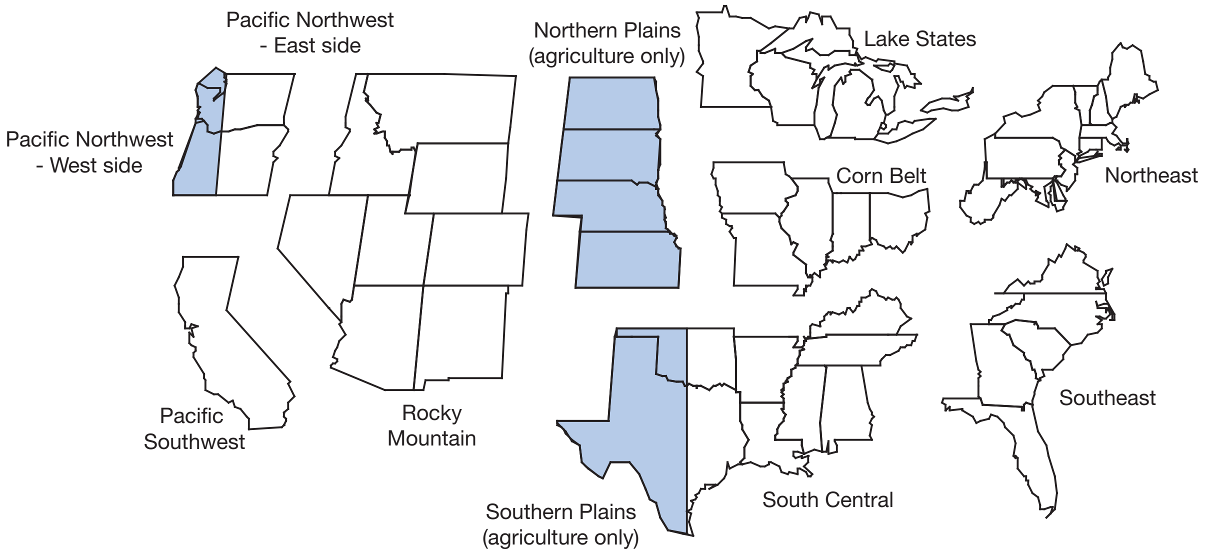
[2] The 10 agricultural regions in FASOMGHG are an aggregation of the 63 agricultural regions considered in the agriculture-only version of this model (ASMGHG) (Schneider 2000).

[3] Timberland is all land with forest cover capable of generating at least 20 cubic feet per acre per year of merchantable timber. Land with forest cover that does not meet this criterion is considered unproductive forestland.

Table 3-2: FASOMGHG Regional Definitions

Key	Name	States
CB	Corn Belt	Illinois, Indiana, Iowa, Missouri, Ohio
NP	Northern Plains	Kansas, Nebraska, North Dakota, South Dakota
LS	Lake States	Michigan, Minnesota, Wisconsin
NE	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
PNWE	Pacific Northwest-east side	Oregon and Washington, east of the Cascade mountain range
PNWW	Pacific Northwest-west side	Oregon and Washington, west of the Cascade mountain range
PSW	Pacific Southwest	California
RM	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
SC	South-Central	Alabama, Mississippi, Louisiana, Eastern Texas, Eastern Oklahoma, Arkansas, Tennessee, Kentucky
SE	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
SW	Southwest	Western Texas, Western Oklahoma

Figure 3 1: FASOMGHG Regions



Box 3-1: Perfect Foresight in Climate Economic Models

Three main approaches to economic modeling of climate change mitigation have been used in the past 2 decades. Engineering cost curves use activity data and cost data to compare and order mitigation practices of technologies by region from lowest to highest cost. Econometric approaches use revealed preferences of landowners for activity and cost data but do not include feedbacks in the land and commodity markets over time. Most climate economic models of multiple sectors, including FASOMGHG, use the third approach, dynamic simulation, which explicitly models economic decisions and market outcomes over time subject to an underlying behavioral or process model.

Weyant (2000) identifies foresight as a key element of structure for dynamic climate economic models, with two prevailing options: perfect and myopic. FASOMGHG employs the perfect foresight option, as do all but one of the climate economic models reviewed by Weyant. Perfect foresight assumes that agents, when making decisions that allocate resources over time (e.g., investments), know with certainty the consequences of those actions in present and future time periods.

Landowners understand that decisions they make today, such as converting agricultural land to trees, depend on their expectations of future prices and yields in forestry and agriculture and, in this case, prices and yields of GHGs. FASOMGHG simulates these decisions and employs these predictions to determine which actions should be taken today and which deferred to the future. As Weyant points out, this form of perfect foresight allows for an efficient allocation of resources over time. These perfect foresight models are also classified as dynamic optimization models. In contrast, myopic foresight uses no predictions of future prices and yields and uses only current information to make decisions that affect resource allocation over time, although not as efficiently as under perfect foresight.

In reality, investors have neither perfect foresight nor perfect myopia, so the modeling decision is not about which assumption is factually correct. In practice, perfect foresight is the approach preferred by most of the climate economic modeling community because of its consistency with economic theory and efficiency. But it is important to understand the implications of the modeling decision. In short, the costs of GHG mitigation estimated using perfect foresight models such as FASOMGHG will tend to reflect a more efficient mitigation response and thus be lower than costs estimated using a myopic foresight model.

of the projection (see Adams et al. [1996]). The terminal value of land remaining in agriculture is formed by assuming that the last period persists forever.

The multiperiod nature of the economic problem requires transforming future revenues and costs to the present using a real (inflation-adjusted) annual *discount rate*. The default rate used in FASOMGHG is 4 percent, which is broadly consistent with opportunity costs of capital in agriculture and forestry.

Forest-Sector Economic Detail

The forest-sector component of FASOMGHG is derived from the USDA Forest Service modeling system for performing periodic assessments of the nation's forests and related renewable resources under the Resources Planning Act (RPA). For more information on the RPA timber market modeling framework, see USDA Forest Service (2003).

Forest Commodities

FASOMGHG tracks the following five forest product categories:

- logs (3): sawtimber, pulpwood, fuelwood
- residues (2): logging and milling

These products are differentiated by two species types (softwood and hardwood) for a total of 10 forest commodities.

Forest Product Supply

Log supply in the model is based on a "model II" even-aged harvest scheduling structure (Johnson and Scheurman 1977) allowing multiple harvest age possibilities. The model's forest inventory is tracked by age, and the harvest responses are limited to even-aged management, wherein a forest stand is grown to a certain age and then harvested and regrown (unless land is allocated to another use after harvest). Timber harvests are responsive to the market price, discount rate, and growth rate of the forest stand. Log supply is volume harvested in each period, so endogenous decisions at the forest level are

[4] The forest production regions include 9 of the 11 regions identified in Table 3-2. The omitted regions are the Northern Plains and Southwest, which do not include any appreciable timber production.

- length of rotation,
- management regime to regenerate the harvested area, and
- species for regeneration.

Supply is segmented into two private-sector classes (industry and nonindustrial private) and nine regions within the United States.[4] Harvests from public lands are included in the model but are exogenously determined, rather than solved by the model.

Timber supply comes from harvests of the merchantable timber inventory existing at that time. The model's timber inventory data are derived from USDA Forest Service Forest Inventory and Analysis (FIA) field data. FIA is essentially a survey of U.S. forests, drawing data from approximately 70,000 field plots nationwide. These field plots have been sampled over time since the 1930s, with survey timing varying by region. The version of the FASOMGHG model used in this report is based on FIA data from the early 1990s.[5] The timber inventory is stratified by the following dimensions:

- region (9),
- land class defining suitability for movement between forestry and agriculture (5),
- ownership (2),
- forest type (4),
- site productivity class (3),
- timber management intensity class (4), and
- 10-year age classes (10).

For timber supply modeling purposes, the critical biophysical element of the timber inventory is the merchantable yield volumes. These volumes are tracked in the inventory data, and FASOMGHG models their evolution over time using the ATLAS model (Mills and Kincaid 1992), which essentially keeps inventory balances over time by tracking for each stratum in the inventory its volume growth, volume harvested, old area out, and new area in. Each stratum is represented by the number of timberland acres and the growing stock volume per unit area.

Forest Product Demand

The 10 forest commodities listed above are the raw materials produced by the forest sector that are ultimately used in the production of final products used by consumers. Therefore, forest commodity demand is characterized as a derived demand for these commodity inputs to the sector's final products. Final product demand is based on the Timber Assessment Market Model (TAMM) (Adams and Haynes 1996) for solid wood products and the North American Pulp and Paper (NAPAP) model (Zhang et al. 1996) for pulp and paper products.

The derived demand system starts with the demand for final products, which include the broad categories of lumber, plywood, oriented strand board (OSB), paper, paperboard, and market pulp, and the demand for wood as a fuel. Final product demand is converted to raw material demand (logs and residues) via physical conversion factors. Substitution is allowed between raw materials in a downward hierarchy from sawlogs to pulpwood to fuelwood, meaning that sawlogs can be used in lieu of pulpwood in pulp and paper production, but not vice versa. Likewise, pulpwood can be used in lieu of fuelwood, but not vice versa. Additionally, mill residues from sawlog processing can be used as a raw material to pulp and paper production. Total raw material demand is bound by sector processing constraints, which is also endogenous to the model.

The product demand functions shift over time as a function of

- macroeconomic factors (gross domestic product [GDP], population, labor force) and
- other key structural shifts:
  - — housing starts,
  - — pulp and paper technical factors (e.g., recycling), and
  - — log conversion factors.

[5] The model is currently being updated to reflect data from the early 2000s.

The macroeconomic and other structural shifts in demand are based on 50-year projections developed for the USDA Renewable Resource Planning Act Assessment and described in its supporting documentation (USDA Forest Service 2003).

International Trade in Forest Products

Canada is the dominant forest products trading partner with the United States, with Canadian exports accounting for a sizable share of total U.S. consumption of softwood lumber and some pulp and paper products, such as newsprint. Therefore, Canada-U.S. final product trade flows are treated explicitly in the model. Exports/imports from countries other than Canada are aggregated as price-sensitive net trade functions facing the U.S. regional markets. Future trade is projected to shift in response to exchange rate projections. The model assumes continuation of the current trade policy environment.[6]

Agriculture-Sector Economic Detail

The agriculture-sector component of FASOMGHG is derived from two predecessors, the Agricultural Sector Model (ASM) (Chang et al. 1992) and ASMGHG (Schneider 2000), both of which are static models of the U.S. agriculture sector. For consistency with the time dynamics introduced by the forest sector, economic decisions in the agriculture sector also conform to the intertemporal welfare maximization approach described above. Agricultural activity within each decade is assumed constant, with dynamic updating each decade based on USDA Economic Research Service (ERS) projections of future yield and consumption trends and past consumption and production trends, where available.

Table 3-3: Agriculture-Sector Commodities

Primary Products
• **Crops:** Cotton, corn, soybeans, soft white wheat, hard red winter wheat, Durham wheat, hard red spring wheat, sorghum, rice, oats, barley, silage, hay, sugarcane, sugarbeets, potatoes, tomatoes for fresh market, tomatoes for processing, oranges for fresh market, oranges for processing, grapefruit for fresh market, grapefruit for processing, rye
• **Animal products:** Grass-fed beef for slaughter, grain-fed beef for slaughter, beef yearlings, calf for slaughter, cull beef cows, milk, cull dairy cows, hogs for slaughter, feeder pigs, cull sows, lambs for slaughter, lambs for feeding, cull ewes, wool, unshorn lambs, mature sheep, steer calves, heifer calves, vealers, dairy calves, beef heifer yearlings, beef steer yearlings, dairy steer yearlings, heifer yearlings, other livestock, eggs, broilers, turkeys
• **Biofuels:** Willow, poplar, switchgrass
Secondary Products
• **Crop related:** Orange juice, grapefruit juice, soybean meal, soybean oil, high fructose corn syrup, sweetened beverages, sweetened confectionaries, sweetened baked goods, sweetened canned goods, refined sugar, gluten feed, starch, refined sugar cane, corn oil, corn syrup, dextrose, frozen potatoes, dried potatoes, chipped potatoes
• **Livestock related:** Fluid milk, grain-fed beef, grass-fed beef, veal, pork, butter, American cheese, other cheese, evaporated condensed milk, ice cream, nonfat dry milk, cottage cheese, skim milk, cream, chicken, turkey
• **Mixed feeds:** Cattle grain mix 0, cattle grain mix 1, high-protein cattle feed, broiler grain, broiler protein, cow grain, cow high protein, range cubes, egg grain, egg protein, pig grain, feeder pig grain, feeder pig protein, pig farrowing grain 0, pig farrowing grain 1, pig farrowing protein, pig finishing grain, pig finishing grain 1, pig finishing protein, dairy concentrate, sheep grain, sheep protein, stocker protein, turkey grain, turkey protein
• **Biofuels:** MMBtu of power plant input, ethanol, market gasoline blend, substitute gasoline blend

[6] For more on forest-sector trade and demand projection assumptions used in FASOMGHG, see USDA Forest Service (2003), Chapter 2.

Agricultural Commodities

The model's agriculture sector encompasses both primary production and secondary processing/ conversion, as indicated in Table 3-3.

Agricultural Product Supply

Primary commodity production is derived from allocation decisions based on a set of more than 2,000 production possibilities for field crops, livestock, and biofuels. The allocation decisions are based on optimizing across the budgets associated with each production possibility, given prices for outputs and inputs. Budgets are based on using inputs to produce a given level of outputs. Land is available in five cropland categories (based on erodibility) plus pastureland. The use of erodibility to classify cropland enables estimation of soil erosion and other environmental effects from different cropping and management practices, as reported in Chapter 7. The land inventory is fixed but can migrate back and forth between agriculture and forestry. Inputs are either regionally supplied subject to a price-sensitive input supply function (labor, grazing, and irrigation water) or nationally supplied at a fixed price (energy, agricultural chemicals, and equipment in more than 100 categories). Supply emanates from 10 regions within the United States.[7]

In the first 2 decades, the production solution is required to be within the combination of crop mixes observed historically, following a method developed by McCarl (1982), but is free to vary thereafter. Agricultural yields and factor usage vary by decade with USDA ERS-projected and historical trends in yield growth and input requirements to sustain this yield growth based on Chang et al. (1992).

Primary commodities are converted to secondary products via processing activities with associated costs (e.g., soybean crushing to meal and oil, livestock to meat and dairy). Processed products and some primary commodities are supplied to meet national-level demands. Once commodities are supplied to the market, they can go to livestock use, feed mixing, processing, domestic consumption, or export.

Agricultural Product Demand

The model uses constant demand elasticity functions to represent domestic and export demand. International agricultural demand is adapted from the USDA SWOPSIM model (Roningen et al. 1991). Domestic demand is drawn from many studies plus computations of arc elasticities from various other sources (Baumes 1978, Burton 1982, Tanyeri-Abur 1990, Schneider 2000, Hamilton 1985). Product demands are updated each decade based on USDA ERS projections and on historic trends where USDA data are unavailable.

International Trade in Agricultural Products

FASOMGHG has explicit trade functions between the United States and 28 distinct foreign trading partners for agricultural commodities having such detailed trade data available. For the remaining commodities traded internationally, excess supply/ demand functions are specified to capture net trade flows with the rest of the world as one composite trade region with the United States. Demand levels are parameterized based on SWOPSIM and USDA annual statistics.

Biofuels

For the purposes of this analysis, biofuels are treated as another agricultural commodity, but as shown in subsequent chapters of the report, they have a rather large potential for GHG mitigation within the sector and thereby warrant special attention. The data used in the analysis for biomass production conditions were mainly obtained from Oak Ridge National Laboratory (ORNL). The data from ORNL include average yields for the three biomass crops (willow, switchgrass, and hybrid poplar) and their corresponding farm-level production costs, varying by state. Estimates of hauling costs are added to the farm-level production costs to complete the budget data needed for the production model.

[7] The agricultural production regions match 10 of the 11 regions identified in Table 3-2. The omitted region is the Pacific Northwest-west side.

On the demand side, special consideration was given to the possibility that infrastructure limitations in the energy sector might impede rapid increase in market penetration for biofuel crops, given the very low use of biofuel crops to date. Therefore, market penetration constraints were imposed on biofuel demand for each decade in the model, with the initial constraints being relaxed over time as more capacity develops. These constraints were developed in consultation with staff from the U.S. Department of Energy's (DOE's) EIA, drawing on work from Haq (2002).[8]

Cross-Sector Land Interaction

A defining element of FASOMGHG is its ability to allocate land across and within the forest and agriculture sectors in response to economic and biophysical forces. As shown in Figure 3-2, the model includes four primary choices of land transfers: from forest to agriculture (cropland or pastureland), agriculture (cropland or pastureland) to forestry, cropland to pasture, and pasture to cropland. Many forested tracts are not suitable for agriculture because of topography, climate, soil quality, or other factors, so the model accounts for land that is not mobile between uses and land that is. Costs for converting forestland reflect differences in site preparation costs because of stump removal amounts, land grading, and other factors.

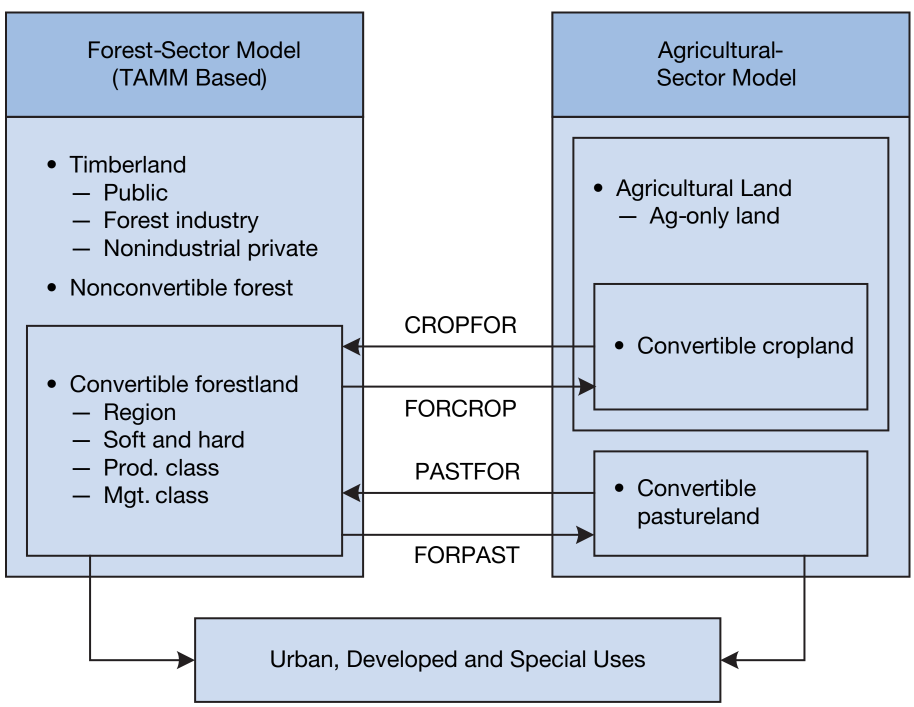
Greenhouse Gas Accounting

Table 3-4 lists the GHG sinks and sources covered by FASOMGHG by sector and gas.

Forest-Sector GHG Accounting

Forest ecosystem carbon accumulates in the forest in four distinct pools: trees, understory vegetation, litter, and soils. The allocation of carbon among these components varies by region, forest type, stand age, site quality, and previous land use. Within FASOMGHG, these allocations are derived from the USDA Forest Service FORCARB model (Birdsey 1992) and Turner et al. (1993). Critical among these relationships is the role of time.

Figure 3 2: FASOMGHG Market Linkages



[8] For more complete model detail on FASOMGHG and its affiliated models, consult Dr. Bruce McCarl's Web site, (http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers.htm).

As described in Chapter 2, once a forest is established, it typically accumulates carbon steadily for several decades, then the sequestration rate begins to decline. If the forest is left in place without harvest or other disturbance, the growth rate may eventually diminish when the forest reaches a steady-state equilibrium.[9] The carbon accounting component of FASOMGHG captures these nonlinear biophysical growth effects.

Additionally, forest carbon accumulates in harvested wood products after it leaves the forest. The carbon can reside in the products while they are being used (e.g., lumber and plywood in housing) or in landfills after the products are discarded and before they decompose and are re-released to the atmosphere. Storage in wood produces can continue for a very long time after harvest. The parameters used to allocate the wood product carbon destination over time after harvest are derived by the HARVCARB model (Row and Phelps 1991).

After it is harvested, carbon can be burned in the production process and released back to the atmosphere. If the burning occurs as part of a combustion process to generate bio-energy, the releases can be viewed as a form of fossil fuel substitution. This form of substitution could be accounted for differently than a normal emission release because it foregoes the transfer of below-ground carbon (coal, petroleum, gas) to the atmosphere, replacing it with "recycled" biofuel. Therefore, FASOMGHG tracks the amount of forest carbon burned for biofuel to examine policy scenarios under which this carbon is treated separately.

The combination of carbon accumulation in forest ecosystems, harvests, releases, product storage, and biofuel energy offsets can create an interesting carbon dynamic over time from the forest sector, as shown in Figure 3-3.

Agriculture-Sector GHG Accounting

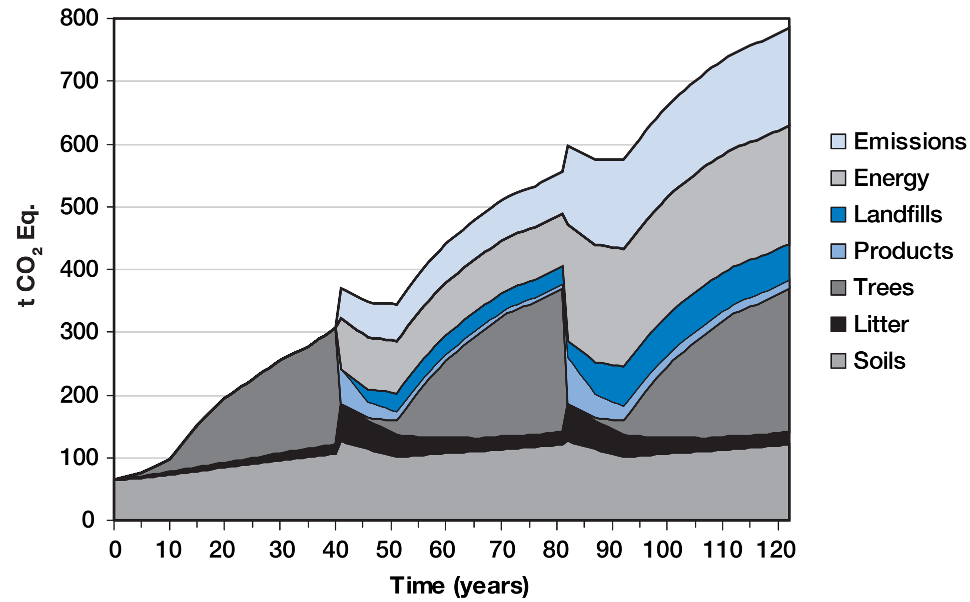
As with forests, carbon accumulates in agro-ecosystems; although in the case of U.S. agriculture, sequestration occurs largely in the form of soil organic carbon (SOC), rather than biomass. FASOMGHG captures SOC changes in response to cropping patterns and tillage changes, based on the CENTURY model (Parton 1996). Three types of tillage are depicted: conventional, minimum tillage, and zero tillage. Four different fertilization

Table 3-4: GHG Emission Sources and Sinks in FASOMGHG

Sector	CO_2 Sinks/Sources (biomass and soil carbon)	Fossil Fuel CO_2	CH_4 Sources	N_2O Sources
Forest	Carbon sequestration and release from forest ecosystems and harvested wood products	Biofuel use in wood processing as a fossil fuel emission offset		
Agriculture	Carbon sequestration and release from agro-ecosystem soils	On-farm energy use	Livestock manure	Fertilizer use
		Energy associated with inputs (e.g., fertilizer production)	Livestock enteric fermentation	Residue burning
		Biofuel production and use as a fossil fuel emission offset	Rice cultivation	Livestock manure

[9] As explained in Chapter 2, this carbon steady state is sometimes referred to as a "saturation point," but equilibrium is a more scientifically precise term. A site can be in steady state, with system inputs and outputs in balance and no net sequestration taking place yet still be able to yield more carbon if, say, inputs were increased by natural (CO2 fertilization) or artificial

Figure 3 3: Cumulative Carbon Changes for a Scenario Involving Afforestation and Harvest



Data Source: Birdsey (1996).

levels are also modeled, and crops are simulated by region. Soil carbon sequestration is assumed to occur at a constant rate for 15 years and then stabilizes thereafter, based on the work of West and Post (2002). Land can move to less intensive tillage with carbon gains or to more intensive tillage with carbon losses.

The agriculture sector releases CO_2 to the atmosphere through the on-farm use of fossil fuels as an energy source (tractors, irrigation, drying operations) and through the upstream emission of fossil fuels in the production of other material inputs such as agricultural chemicals using calculations from Schneider (2000) based on USDA data.

The agriculture sector is a major source of the non-CO_2 gases—CH_4 and N_2O. CH_4 releases in agriculture are from enteric fermentation, manure management, and rice cultivation. Enteric fermentation emissions and emission changes from the baseline are estimated using data based on EPA data and a set of alternatives proposed by Johnson et al. (2003a, 2003b), involving changes in feeding regimes, improved pasture use, and use of bovine somatrophine (bST). Manure emissions are estimated using swine and dairy farm data estimated for digester use based on EPA data. Rice CH_4 emission are estimated using data used to support the U.S. national GHG inventory (EPA 2003). N_2O sources in agriculture come from fertilizer use, residue burning, and livestock manure. These N_2O releases are estimated using U.S. activity data with IPCC emissions factors.

Difference in Scope of GHG Accounting in the Forest and Agriculture Sectors

Forest-sector GHG accounting in FASOMGHG does not include CO_2 emissions from on-site machinery and upstream processing of inputs, CH_4 emissions from forested wetlands or landfilled forest products, nor N_2O emissions from fertilizer use. Most of emissions data for these activities or sources are not readily available for the forest sector. Thus, the GHG accounting for the forest sector has a narrower scope than for the agriculture sector in FASOMGHG. However, the omitted emissions in the forest sector are generally thought to be small relative to those included, so their omission is unlikely to create a distorted view of mitigation potential in this report.

Non-GHG Environmental Indicators

Several variables discussed above provide useful information on environmental quality implications of modeled outcomes. In the forest sector, these include forest land area composition by species and age class, forest management intensity, and rotation length (harvest age). Land-use and management patterns are also reported on the agriculture side of the model. In addition, the model draws from the agricultural management model EPIC (Williams et al. 1989) to produce data on irrigated acres and water use and on cropland loadings of nitrogen, phosphorous, potassium, erosion, and pesticide use.

GHG Mitigation Strategies

The comprehensive coverage of FASOMGHG allows for the identification of several basic strategies for GHG mitigation in forestry and agriculture. Table 3-5 lists broad mitigation strategies aligned with specific mitigation activities tracked by FASOMGHG. These strategies are a mix of sequestration, emissions reduction, and fossil fuel offsets. Although each strategy has a focal GHG of interest, it is important to recognize that FASOMGHG incorporates multi-GHG accounting and therefore captures the net GHG consequences of each strategy. This is particularly critical given that GHG policies may include only a subset of GHGs, as discussed further in Chapter 5.

While FASOMGHG is fairly complete in its coverage of GHG mitigation opportunities in U.S. forestry and agriculture, some mitigation opportunities remain outside the scope of the model. Of those activities referenced in Chapter 2, two warrant further discussion here (see Table 3-6).

First, the model does not consider forest management opportunities on the 275 million acres (37 percent) of all forestland in the United States in public ownership (Smith et al. 2001). Assuming all of those acres could be managed to achieve the carbon enhancements for forest management

Table 3-5: Broad GHG Mitigation Strategies Covered in FASOMGHG

Strategy	Mitigation Activities Tracked in FASOMGHG	Target GHG
Afforestation	Convert agricultural lands to forest	CO_2
Forest management	Lengthen timber harvest rotation Increase forest management intensity Forest preservation Avoid deforestation	CO_2
Agricultural soil carbon sequestration	Crop tillage change Crop mix change Crop fertilization change Grassland conversion	CO_2
Fossil fuel mitigation from crop production	Crop tillage change Crop mix change Crop input change Irrigated/dry land mix change	CO_2
Agricultural CH_4 and N_2O mitigation	Crop tillage change Crop mix change Crop input change Irrigated/dry land mix change Enteric fermentation control Livestock herd size change Livestock system change Manure management Rice acreage change	CH_4 N_2O
Biofuel offsets	Produce crops for biofuel use	CO_2

Table 3-6: Mitigation Options Not Explicitly Captured in FASOMGHG

Option	Description	Maximum Biophysical Mitigation Potential	Economic and Other Adoption Factors
Forest management on public lands	Enhancing forest carbon through changes in management of publicly owned forestlands	~685 Tg CO_2 per year (275 MM acres at 2.5 t CO_2 per acre per year)	Public lands are by mandate managed for multiple uses, implying an opportunity cost of managing specifically for carbon. Allowable federal timber harvest levels set by Congress could have a large impact on baseline levels of carbon storage.
Grazing land management	Improving forage quantity and quality to retain more soil carbon	~590 Tg CO_2 per year (590 MM acres of nonfederal pasture/ rangeland at 1 t CO_2 per acre per year)	Limited data are available on the cost of adopting practices and corresponding carbon and other GHG effects.

referenced in Chapter 2 (roughly 2.5 t CO_2 per acre per year), this could hypothetically enhance forest carbon sequestration by nearly 700 Tg CO_2 per year.

However, this maximum biophysical potential estimate has little meaning. The biophysical productivity of public forestlands is generally lower than private lands, and this is an estimate of pure biophysical potential, without considering economic or other institutional factors. There is no information on the costs of achieving this mitigation on public forests. Moreover, the analyses in this report gauge the response of the forest and agriculture sectors to GHG prices or market incentives, essentially a private-sector phenomenon. Public land responses are possible but require public land management legislative mandates (e.g., changes in national or state forestland harvest or planting levels) that are fundamentally different from the market-based approaches addressed in this report.

Another set of strategies not captured in FASOMGHG is grazing land management practices. Grazing land includes rangeland, pastureland, and grazed forestland. The United States has about 590 million acres of nonfederal grazing land (USDA NRCS 2000). Little data exist on either the carbon sequestration effects or costs of these changes in practices. Using a mid-range estimate of 1 t CO_2 per acre per year for grazing practices from Chapter 2, this suggests a maximum biophysical potential for mitigation of nearly 600 Tg CO_2 per year. But again, little data are available from which to conduct economic analyses of these options. In addition, changes in grazing practices could be adopted on federal lands, but limited information is available on the area of land to which these practices could be applied, the cost, and the consistency with other public land management objectives.

One other category of practices that is implicitly captured in FASOMGHG but is not broken out separately is riparian buffer establishment. As indicated above, riparian buffers are the establishment of vegetative cover such as grass or trees near water bodies. The model captures afforestation and grassland conversion, but it does not have the data to determine whether those conversions are taking place in riparian areas. Therefore, the model will implicitly capture establishment of trees and grasses in this area in response to the GHG incentives put forth (e.g., GHG price payments), but it will not be able to identify this distinctly as riparian buffers. As a result, the model cannot currently examine policies specifically aimed to increase riparian buffers.

Baseline GHG Projections from the Forest and Agriculture Sectors

The estimation of a baseline is an important first analytic step for this study, because the analyses of GHG mitigation potential presented in subsequent chapters must be measured against a credible baseline reflecting a continuation of BAU activity.

The analysis begins by using the FASOMGHG model to simulate future economic activity and corresponding GHG effects in the forest and agriculture sectors under a continuation of the status quo, or BAU. Departures from this baseline constitute the mitigation quantities estimated in response to the price and policy scenarios analyzed throughout this report.

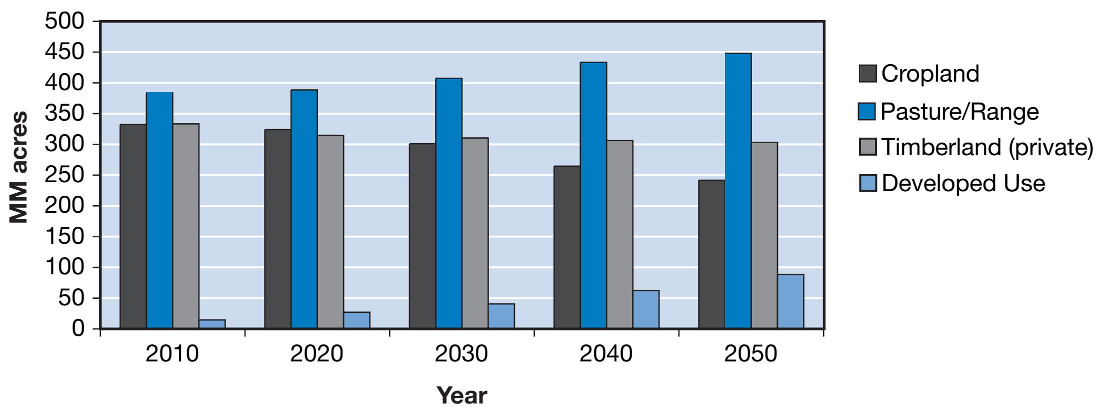
FASOMGHG Baseline Projections

This section presents baseline projections from the FASOMGHG model. These results reflect model outputs when FASOMGHG is run based on the exogenous data and trends discussed above and without any GHG policies in place. We look first at projections of key land-use and management trends and see how these comport with trends reported in recent land-use inventory data. We then look at the FASOMGHG projections of the sectors' GHG flows (emissions and sequestrations) and compare these projections with other secondary sources as well.

Baseline Land-Use and Management Projections

One of the driving factors of the GHG effects in these sectors is how land is expected to be used over time. FASOMGHG simulates land allocation for each region across time. National-level projection of land use across the major categories of cropland, pasture/range, timberland, and developed use is illustrated in Figure 3-4. Cropland is projected to decline steadily into the future as productivity improvements reduce the demand for cropland relative to other uses. This is a continuation of recent history, as discussed below. Pasture/range land is projected to rise over time, as demand for livestock products is projected to grow. Timberland is projected to decline just modestly over time, as demand for timber attracts some land from agriculture, but losses of land to developed use occurs.[10] Developed use is projected to grow substantially over time, attracting land from both forestry and agriculture and thereby reducing, to some extent, the capacity of the forest and agriculture sectors to mitigate GHGs through actions on the land base.

Figure 3 4: Baseline Land Use Projections, FASOMGHG: 2010 2050 (Million acres)



[10] The FASOMGHG projections for timberland out to 2050 are lower than those projected by the USDA Forest Service in their most recent RPA projection (USDA Forest Service 2003, Ch. 2, Table 5) primarily because of differences in coverage—the latter includes all 50 states, while the former includes the 48 contiguous states only. However, FASOMGHG projects a 9 percent loss of timberland between 2010 and 2050, while the USDA Forest Service projects a 4 percent loss of timberland. The economic forces captured by FASOMGHG suggest a more fluid change in land use than the USDA Forest Service methods.

As indicated above, FASOMGHG projections for declining cropland are consistent with recent trends observed in the United States. Table 3-7 reports data from the NRI, which tracks land-use change across major categories from 1982 to 1997. The biggest single change was in the area of cropland—a net loss of about 44 million acres (10.4 percent of the 1982 total). NRI data (not shown in the table) indicate that three-quarters of the 1982 to 1997 cropland loss total was diverted to CRP lands (about 33 million acres); the remaining lost cropland is net transfers to pasture and range, forestland, developed, and other uses. The CRP was established to remove cropland from production that is highly susceptible to erosion or otherwise unproductive. In the scenarios throughout this report, CRP land is assumed to remain permanently at the initial level of 33 million acres.

Factors Underlying Land-Use Change Trends

For private lands in a market economy, land-use decisions generally reflect each landowner's desire to maximize the utility obtained from his or her land by trying to maximize land profits (also called land "rents"). These landowners may be very responsive to changes in commodity output prices and input prices and make land management decisions to change the products they produce and the inputs they use as prices vary. Other landowners may place more emphasis on the nonmarket services provided by their land such as rural lifestyles, or wildlife habitat, more than maximizing the land's net income (Birch and Moulton 1997). These landowners may be less responsive to constantly changing market signals than more profit-oriented landowners. Over time these market signals—including GHG market price signals addressed in this report—may affect the landowner's land-use decisions under changing market and nonmarket conditions. Farmers may adopt conservation tillage practices, establish buffers along riparian corridors, and retire unproductive lands independent of, or in response to, market incentives for GHG mitigation.

Price trends in forestry and agricultural commodities or technological advances in equipment and land management options may be the largest factors influencing land-use change for rent-driven landowners. Figure 3-5 plots estimates of total

Table 3-7: U.S. Land-Use Change for Major Categories: 1982–1997

	Million Acres			
Land Cover/Use	**1982**	**1997**	**Change**	**Percent**
Cropland	420.6	376.7	–43.9	–10.4%
Conservation Reserve Program (CRP)	0.0	32.7	32.7	—
Pasture	131.9	119.9	–12.0	–9.1%
Rangeland	416.4	405.7	–10.8	–2.6%
Forestland[a]	403.0	406.6	3.6	0.9%
Other rural land	49.6	51.1	1.5	3.0%
Developed land	73.2	98.2	25.0	34.1%
Water areas and federal land	447.9	451.8	3.9	0.9%
Total	1,942.6	1,942.6	0.0	—

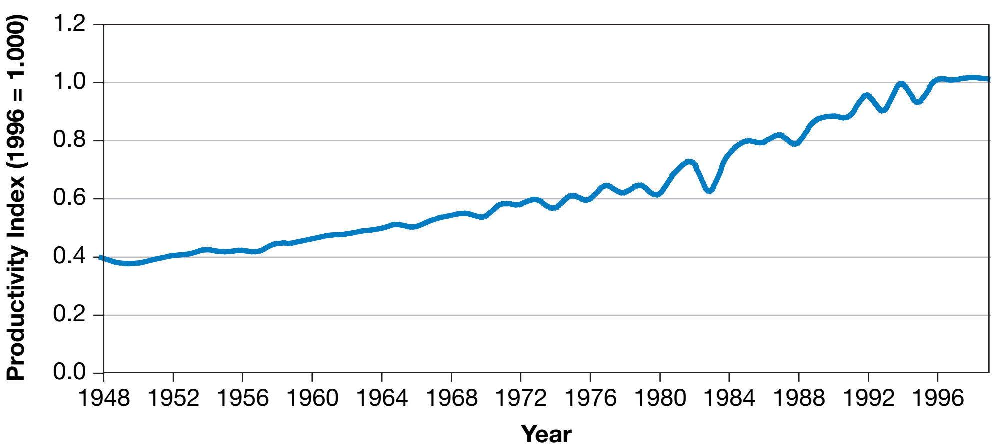
Source: USDA NRCS (2000).

[a] Forestland tracked by USDA, NRCS encompasses all productive timberland, as defined by USDA Forest Service, and reported in Table 3-6, plus forestland that is not considered productive enough to be timberland.

factor productivity in U.S. agriculture over the last half of the twentieth century,[11] averaging 1.8 percent per year. However, from 1979 to 1999, the average annual increase in productivity was about 2.3 percent.

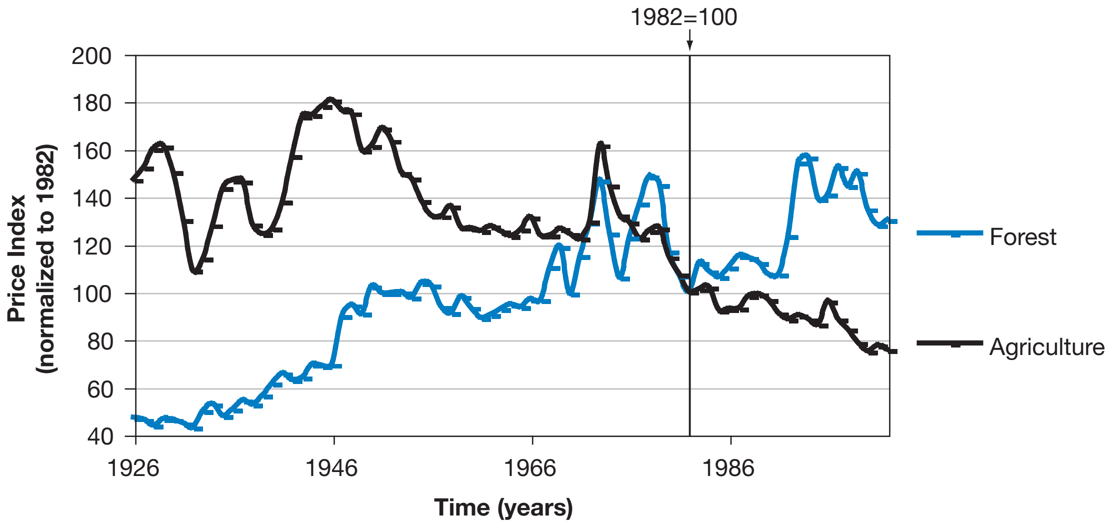
During this period, real agricultural prices (i.e., net of inflation) have trended downward; net farm income has stayed about even; and, as discussed above, land devoted to agriculture has dropped. Increases in agricultural productivity have reduced the amount of land needed for agriculture, leading to land retirement (CRP) and movement to pasture/range, timberland, or developed uses. As shown in Figure 3-6, the rise in forest-sector prices relative to agricultural prices provides incentive for that movement of land, along with increases in population and real income.

Figure 3 5: Total Factor Productivity in U.S. Agriculture: 1949 1998



Source: Ball, Butault, and Nehring (2001).
Data for figure downloaded from http://www.ers.usda.gov/data/agproductivity/.

Figure 3 6: Forest and Agriculture Products Price Series



Source: U.S. Department of Labor, Bureau of Labor Statistics (Annual Series).

[11] Total factor productivity measures the relative change in the ratio of total output produced to all inputs used. It is a comprehensive measure of productivity and is a standard measure of technical efficiency in production.

Another significant driver of land-use change is population growth. Population grew about 24 percent in the United States between 1980 and 2000 (Hobbs and Stoops 2002). Table 3-7 provides evidence of population's effect on land use: developed land uses experienced the highest increase between 1982 and 1997, with 25 million acres of land undergoing development during that time period, an increase of more than one-third.

Baseline GHG Projections

Table 3-8 presents the FASOMGHG baseline projection of net GHG emissions from the U.S. forest and agriculture sectors for decades 2010 to 2050 by specific activity group. The table reveals that the sectors host a unique mix of activities. Some activities, on balance, remove more GHGs from the atmosphere than they emit (e.g., forest carbon and, in some cases, agricultural soil carbon sequestration). Some are pure emission sources (e.g., CO_2 emissions from fossil fuel use, agricultural CH_4 and N_2O emissions). A small amount of baseline biofuel (biomass) offsets is expected to be generated in the form of ethanol substitution for liquid fuels. The net atmospheric GHG effect is negative (GHG removal), because these renewable biofuels replace the burning of fossil fuels.

To summarize, the most important baseline sectoral GHG effects over time are the following:

- The private forest sector is a net carbon sink, absorbing more CO_2 than it releases through harvests and land-use change. The sink effect, though, is projected to diminish in magnitude over time, from 436 Tg CO_2 per year in 2010 to 170 Tg CO_2 per year in 2050. In the baseline, there is some afforestation taking place in the

Table 3-8: Baseline Forest and Agriculture GHG Net Annual Emissions by Activity and Decade for the United States: FASOMGHG Model: 2010–2050

	2010	2020	2030	2040	2050
Forest-sector (private) sources/sinks[a]	**(436)**	**(222)**	**(145)**	**(225)**	**(170)**
Afforestation	(114)	92	18	4	26
Forest management	(322)	(314)	(163)	(229)	(196)
Agriculture-sector sources/sinks (direct)[b]	**521**	**513**	**477**	**449**	**459**
Agricultural soil carbon sequestration	32	10	(83)	(148)	(167)
Agricultural CH_4 and N_2O	489	503	560	597	626
Sources/sinks from agriculture-energy sector linkages[c]	**186**	**189**	**202**	**218**	**231**
Fossil fuel from crop production	197	200	213	229	242
Biofuel offsets	(11)	(11)	(11)	(11)	(11)
Combined forest- and agriculture-sector net GHG emissions[d]	**270**	**479**	**535**	**442**	**520**

[a] Sum of afforestation and forest management.

[b] Sum of agricultural soil carbon sequestration and agriculture CH_4 and N_2O.

[c] Sum of fossil fuel from crop production and biofuel offsets.

[d] Sum of three categories above.

Notes: All quantities are in Tg CO_2 Eq. per year. Negative (parenthesized) values are removals from the atmosphere (sinks). Positive (nonparenthesized) values are emissions to the atmosphere (sources); decade means annual average value for that decade. Some rounding error may occur.

first decade but not beyond that. Consequently, future decades show losses in carbon accumulated since the base year because of harvesting of the afforested lands.[12]

- Net "direct" agricultural GHG emissions—the sum of agricultural non-CO_2 emissions and soil carbon sequestration—exceed 500 Tg CO_2 per year in the baseline's first decade but eventually decline. Non-CO_2 emissions are projected to rise steadily throughout the projection period, but this rise in emissions is expected to be offset by soil carbon sequestration, which starts as a source but becomes a sink in later years. By 2050, agricultural soil carbon sequestration draws even with forest carbon sequestration at about 170 Tg CO_2 per year.
- Net emissions from agriculture attributable to energy production include CO_2 emissions from fossil fuel use in agricultural inputs offset by biofuel production in agriculture. Together, these factors are projected to account for 186 Tg net CO_2 per year in the 2010 decade, rising to about 230 Tg CO_2 per year in the 2050 decade, a gain of about 25 percent.
- Combining all direct and indirect sources and sinks in the combined forest and agriculture sectors, the model baseline is somewhat variable over time. The substantial drop in baseline forest carbon sequestration over the first 2 decades causes a substantial increase in the combined forest- and agriculture-sector net GHG baseline emissions, essentially doubling between 2010 and 2030 (270 to 535 Tg CO_2 per year). This GHG build-up reverses direction after 2030, as carbon sequestration from both forests and agricultural soils overtakes the rise in sector GHG emissions.

Comparison of FASOMGHG Baseline GHG Projection to Other Published Estimates

Several estimates exist of historic and projected GHG trends in U.S. forestry and agriculture, including those reported by EPA, USDA Forest Service, and others. We review these estimates here and compare them to the baseline used in the FASOMGHG model.

Forest Carbon Sequestration

For forest carbon, we rely on two principal baseline studies that have estimated past, current, and projected carbon sequestration rates of American forests:

- U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990 – 2003* (EPA 2005)
- USDA Forest Service, *Carbon Sequestration in Wood and Paper Products* (Skog and Nicholson 2000)

EPA GHG Inventory Baseline. The national GHG inventory (EPA 2005) reports GHG emissions and sinks in the United States since 1990. Table 3-9 shows the net flux in CO_2 equivalents resulting from forestry activities, including the amount of carbon stored in harvested wood products. This combined forest + wood products measure is the most directly comparable to the FASOMGHG forest carbon measure. Together, the forest carbon sink components account for over 90 percent of all terrestrial carbon sequestration in the inventory; the remaining portion comes from agricultural soil carbon. Carbon contained in wood products constitutes about one-quarter to one-third of the total forest carbon sequestration total.

The total forest carbon flux reported in the EPA inventory declined steadily from 1990 to 2000. In 1990, the sector generated a net sink of nearly 950 Tg CO_2 Eq. per year, but this declined by about 200 Tg per year by 2000. Two-thirds (137 Tg CO_2 Eq. per year) of the decline in sequestration from 1990 to 2000 is attributable to a change in the methods used to estimate SOC between the two periods. The remaining third (64 Tg) is attributable to a reduced rate of afforestation, which was quite high in the late 1980s and early 1990s partly because of public conservation programs such as the CRP.

[12] The base year for these simulations is 2000. Model results are reported for the period 2010 to 2050 (see Chapter 4). Some of the carbon losses from "afforestation" are based on lands afforested in the 2000 decade.

Table 3-9: Net Annual CO_2 Flux from U.S. Forest Carbon Stocks: 1990 and 2000, EPA Inventory Quantities (in Tg CO_2 per year)[a]

Component	1990	2000
Forest	(739)	(537)
Above ground	(396)	(400)
Below ground	(77)	(78)
Dead wood	(74)	(45)
Litter	(67)	(26)
Soil organic carbon (SOC)[b]	(125)	12
Harvested wood	(210)	(211)
Wood products	(48)	(59)
Landfilled wood	(162)	(152)
Total net annual flux	(949)	(748)
Difference in net flux: 2000 vs. 1990		201
Difference, net of SOC		64

Source: EPA (2005).

[a] Negative (parenthesized) values are removals from the atmosphere (sinks). Positive (nonparenthesized) values are emissions to the atmosphere (sources).

[b] SOC differences are primarily due to changes in estimation methods.

USDA Forest Service Forest-Sector Baseline. The estimates in the EPA inventory report recent historical trends since 1990, but future projections are necessary for comparison against the FASOMGHG baseline. EPA estimates for the forest sector were derived collaboratively with the USDA Forest Service, using USDA Forest Service models referenced above (e.g., FORCARB). Therefore, we turn to a recent study by USDA Forest Service researchers that estimates national levels of forest carbon sequestration into the future to provide a consistent framework for comparison.

In 2000, the USDA Forest Service produced a comprehensive assessment of national forest carbon stocks and flows. Within that report, a chapter by Skog and Nicholson (2000) presents a set of projections for the period 1990 to 2040 that can be matched to the forest carbon categories reported by EPA above. The USDA Forest Service projections are presented in Table 3-10. According to those estimates, U.S. forest carbon sequestration exceeded 1.2 Gt CO_2 per year in 1990, at which point a steady decline is projected to extend but taper off through the middle of the 21st century. The forest sink is projected to decline about 360 Tg CO_2 per year (30 percent) from 1990 to 2040. But virtually all of that decline is found in the 1990 to 2000 decade, mirroring the drop reported in the EPA GHG inventory for that same time period. The projected annual decline in forest carbon sequestration from 2000 to 2040 is just 5 percent.

Table 3-10: Projected Net CO_2 Flux from U.S. Forest Carbon Stocks: 1990–2040, USDA Forest Service Estimate

	Net CO_2 Flux (Tg CO_2 per year)					
	1990	2000	2010	2020	2030	2040
Change in forest carbon stocks	1,006	694	705	646	609	591
Changes in harvested wood carbon stocks	218	211	235	250	261	270
Change in products in use	96	92	90	94	89	84
Change in landfills	123	119	145	156	172	186
Total change in stock of carbon	1,224	905	939	896	870	861

Source: Table 5.7 in Skog and Nicholson (2000).

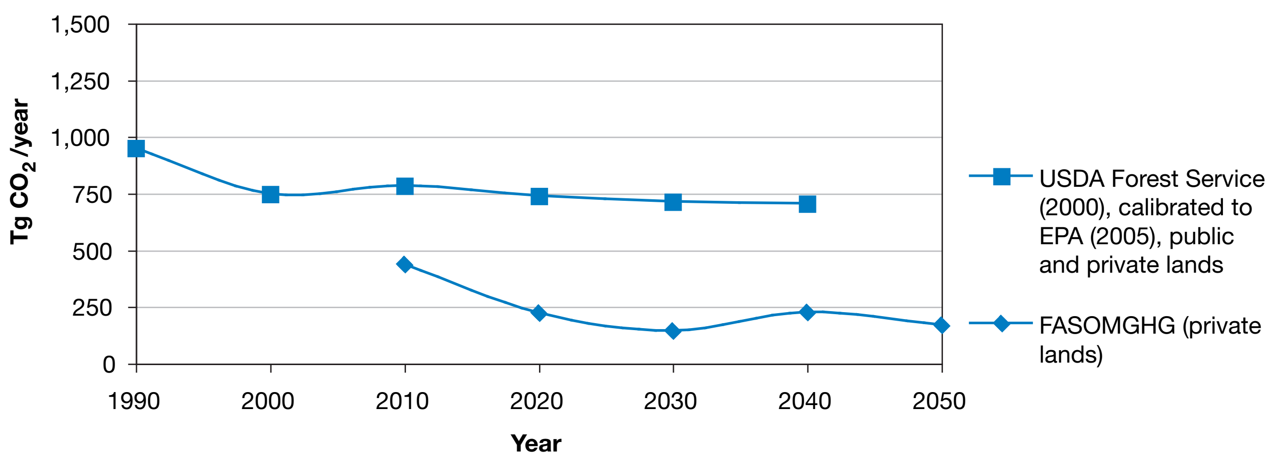
Comparison of Baseline Projections: USDA Forest Service and FASOMGHG. We now compare FASOMGHG's forest carbon baseline projections with projections for the corresponding time period by USDA Forest Service (Skog and Nicholson 2000). The comparison is illustrated in Figure 3-7.

Before proceeding with the comparison, we note several important points. First, the projection time periods do not exactly match: the USDA Forest Service projections run from 1990 to 2040, and FASOMGHG's projections run from 2010 to 2050. Therefore, the most meaningful comparisons are from 2010 to 2040. Second, in Tables 3-9 and 3-10 note the difference in the quantities between the EPA and USDA Forest Service estimates for 1990 and 2000. The 2000 value reported in the USDA Forest Service report is more than 150 Tg CO_2 higher than the EPA inventory estimate. Much of this difference is due to the methods-based adjustment in soil carbon estimates between 1990 and 2000 that is reflected in the EPA (2005) estimate but not in the Skog and Nicholson (2000) estimate. Because this soil adjustment is methodological in nature, we recalibrated the Skog and Nicholson projections to be more consistent with the EPA projection using the revised methodology. We did that by adjusting the USDA Forest Service projection downward to match the EPA estimate for 2000 (748 Tg CO_2) and then allowing the USDA Forest Service projection for 2000 to 2040 to pertain beyond that.

Third, the USDA Forest Service projections are for *all* forestland in the United States (private and public), while the FASOMGHG projections are for *private* land only. Although the inventory data for public forestland are somewhat incomplete, these forests are estimated to provide a substantial net carbon sink in the United States (Heath 2000). That essentially explains the large gap between the FASOMGHG and USDA Forest Service lines in Figure 3-7.

Putting aside the public lands gap in Figure 3-7, both sets of projections show a similar pattern, namely that the forest carbon sink is projected to decline over time. The decline is a bit more pronounced in FASOMGHG, reflecting differences in the methods used to create the projections. FASOMGHG uses economic principles and dynamic optimization methods to allocate resources across time, while the system used by Skog and Nicholson is not as explicitly driven by economic models of intertemporal economic behavior. However, both sets of projections are consistent in their assessment that under BAU

Figure 3 7: Comparison of Projected Baseline Carbon Sequestration Trends in U.S. Forests: FASOMGHG vs. USDA Forest Service Model



conditions, the rate of CO_2 sequestration in U.S. forest ecosystems is slated to decline over time. Therefore, absent any policy interventions or unforeseen changes in natural, economic, or institutional phenomena, the forest sector's role in partly offsetting the country's GHG emissions will diminish.

To summarize, forests make up the lion's share of current terrestrial sequestration in the United States and are a net sink because the amount of CO_2 currently taken up through photosynthesis and stored in biomass, soils, and products exceeds the amount released through harvesting and natural disturbances. This is the result of recent land-use trends, which show a net movement of land from agriculture to forests, and an age class structure of U.S. forests favoring younger, faster-growing trees. However, under BAU, these land-use conversions are not expected to occur at the same rate. Additionally, timberland is projected to be diverted to developed uses over the projection period, thereby leading to forest carbon losses. Taking these factors together, future sequestration rates in the U.S. forest sector are expected to decline below the rates we are now experiencing in the absence of additional forest carbon sequestration activities.

Agricultural Soil Carbon Sequestration

As was shown in Table 3-8, FASOMGHG projects agricultural soil as a net emitter of CO_2 in the early periods (about 30 Tg CO_2 in 2010) and as a significant sink in later years (nearly –170 Tg CO_2 in 2050), thereby tipping the sector's carbon balance toward sequestration by about 200 Tg CO_2 during this time period.

Although there are no published projections of future baseline agricultural soil carbon sequestration to compare with the FASOMGHG projections for 2010 to 2050, one can compare the 2010 projection—a small source of +32 Tg CO_2/year—with the most recent estimate (for data year 2003) reported in the U.S. GHG inventory (EPA 2005)—a small sink of –7 Tg CO_2/year. This gap reflects a difference between methods used in FASOMGHG (i.e., CENTURY model) and methods used in the EPA inventory (IPCC default factors with U.S. data), and assumptions on short-run baseline adoption of practices to sequester agricultural soil carbon. The FASOMGHG model reveals a pattern of low adoption of sequestration practices (predominately reduced tillage) in the early years of the projection but robust adoption in later years in response to projected changes in the underlying market and technological conditions. The EPA inventory estimates may reflect some adoption occurring sooner than projected in the FASOMGHG model. Other differences in underlying phenomena involving soil sequestration also may be occurring, such as the rate of cropland conversion to grassland and changes in nontillage soil management, including the addition of manure amendments.

Non-CO_2 GHG Emissions in Agriculture

According to the national GHG inventory report (EPA 2005), agricultural practices directly account for about 6 percent of all GHG emissions in the United States, primarily in the form of CH_4 and N_2O. These non-CO_2 GHG emissions from agriculture totaled about 433 Tg CO_2 Eq. in 2003 (see Table 3-11). As discussed earlier in this report, the primary sources of these GHGs in agriculture are fertilizer applications on croplands, enteric fermentation, manure management, and rice cultivation. Residue burning is also a small source of non-CO_2 gas emissions from agriculture. According to the national GHG inventory report, agriculture accounted for about 30 percent of all CH_4 emissions and 72 percent of all N_2O emissions in the United States.

Table 3-11 presents recent levels of agriculture non-CO_2 GHG emissions. The trends presented in Table 3-11 show a fairly slight (1.6 percent) increase in sector emissions between 1990 and 2003. Although they have increased, agricultural emissions have done so at a slower rate than total U.S. GHG emissions (EPA 2005).

Although the EPA inventory estimates are historic, a recent paper by Scheehle and Kruger (in press) provides projections for non-CO_2 GHG emissions out to 2020. Those projections are compared to the FASOMGHG projections in Figure 3-8 and are found to match rather well. The magnitudes of the estimates are within 5 percent of each other and both show a rising trend in non-CO_2 emissions over the next several decades.

Sources/Sinks from Agriculture-Energy Linkages

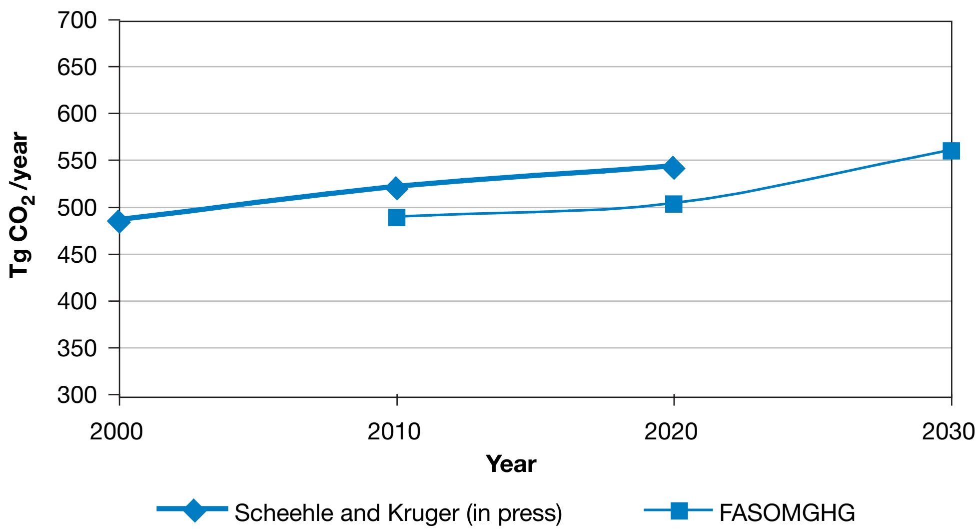
As reported in Table 3-8, a sizeable portion of the sector's total emissions originate from CO_2 released in fossil fuel combustion embodied in the energy to produce agricultural inputs. As described above, this not only includes on-farm use of fuels in farm machinery, but also the upstream energy use in the production of inputs, such as the amount of energy used to produce fertilizer. This is a more expansive definition of agricultural CO_2 emissions than others have employed and therefore there are no direct

Table 3-11: Non-CO_2 GHG Emissions from Agriculture (Tg CO_2 Eq.): EPA GHG Inventory, 1990–2003

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**156.9**	**163.0**	**164.2**	**164.6**	**162.0**	**161.9**	**161.5**	**161.8**
Enteric fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0
Manure management	31.2	36.4	38.8	38.8	38.1	38.9	39.3	39.1
Rice cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9
Agricultural residue burning	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.8
N_2O	**269.6**	**269.8**	**285.6**	**261.3**	**282.1**	**275.6**	**270.9**	**271.5**
Agricultural soil management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5
Manure management	16.3	17.3	17.4	17.4	17.8	18.0	17.9	17.5
Agricultural residue burning	0.4	0.4	0.5	0.4	0.5	0.5	0.4	0.4
Non-CO_2 GHG Emissions Total	**426.5**	**432.8**	**449.8**	**425.9**	**444.1**	**437.5**	**432.4**	**433.3**

Note: Totals may not sum due to independent rounding.
Source: These numbers are taken from EPA (2005).

Figure 3 8: Comparison of Projected Baseline Non CO_2 GHG: FASOMGHG vs. Scheehle and Kruger (in press)



comparisons that can be made to the FASOMGHG estimate. The closest comparison one can make is to the 2005 EPA GHG inventory, which shows CO_2 emissions from agricultural equipment of about 41 Tg CO_2 per year in 2003 (EPA 2005, Table 3-36 in Annex 3-2).

Applying FASOMGHG for the Purposes of this Report

FASOMGHG evaluates the joint economic and biophysical effects of GHG mitigation policies in the U.S. forest and agriculture sectors. The model considers most major GHG mitigation options and GHG flows in the two sectors over an extended time period. As an economic model, FASOMGHG ensures consideration of the effects of policy initiatives on resource flows and economic activities within and across the forest and agriculture sectors over time. It has sufficient detail to answer questions about which activities are economic, how much GHGs are reduced by their adoption, and where and when the actions are likely to occur. Interpretation of the model results can provide insights into how and why these activities and GHG effects occur.

FASOMGHG and its component models have been extensively peer reviewed.[14] The model is consistent with modern economic theory, agronomy, and ecology. FASOMGHG is empirically grounded with base period data (ca. 1990 to 2000) tied to published projections of key data and parameters for simulation of future scenarios.

The comprehensiveness, detail, theoretical consistency, and empirical grounding of FASOMGHG make it suited for policy analyses of GHG policies, including the introduction of GHG (sometimes called carbon or CO_2) prices, GHG quantity goals, and nuanced combinations thereof. Like any model, some abstraction of real-world complex details is necessary to make the problem tractable, which can hinder the flow of some information. Therefore, one may want to focus more on the broad and subtle patterns found in the model results and what they mean for GHG policy, rather than on specific estimates of a GHG or economic effect at a certain point in place and time.

[14] For a selected listing of publications using FASOMGHG and its predecessor models (ASM and FASOM), see http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers.htm.

CHAPTER 4

Mitigation Potential: Comprehensive Scenarios with All Activities and All GHGs

Chapter 4 Summary

Mitigation results are presented for all forest and agricultural activities and all GHGs under constant and rising GHG price scenarios over a range of \$1 to \$50 per t CO_2 Eq. (or roughly \$4 to \$184 per t C Eq.). Mitigation quantities are reported as changes from FASOMGHG's baseline. Low GHG price incentives have little effect on land-use change, but higher prices can induce substantial land-use change from agriculture to forestry and changes in practices within sectors. The price level affects the optimal portfolio of mitigation strategies. Carbon sequestration from agricultural soil practices and forest management dominates at lower GHG prices and in the near term. These two options produce about 90 percent of all mitigation in the earlier years, but these annual sequestration effects diminish by 2055. Afforestation dominates mitigation at higher prices in the early to middle years. However, carbon sequestered in afforestation is reversed by 2055, at which time the planted forests become a net CO_2 source. At the highest prices and in the later years, biofuels are a dominant strategy.

Timing effects vary depending on the GHG price scenario. In the constant-price scenarios, GHG mitigation declines over time, as landowners react early to incentives. Declining rates of mitigation are the result of carbon saturation (reaching a new equilibrium), harvests, and the conversion of forests back to agriculture. Despite these declining annual mitigation rates, cumulative mitigation steadily increases. In the rising-price scenarios, GHG mitigation increases over time as landowners are assumed to fully recognize that prices will rise and therefore employ some mitigation actions later. Mitigation potential has a regional distribution. The South-Central, Corn Belt, and Southeast regions possess the largest GHG mitigation potential, while the Rockies, Southwest, and Pacific Coast regions generate the least.

Chapter 3 describes the modeling framework of FASOMGHG and its projected baseline of GHG emissions and sinks in U.S. forestry and agriculture. This chapter presents FASOMGHG mitigation results as changes from the baseline, in terms of additional carbon sequestration and GHG reductions. Mitigation results are presented for a range of hypothetical scenarios that include both constant and rising economic incentives for GHG mitigation over time. More specifically, results from the GHG mitigation scenarios show management and land-use changes, average annual GHG mitigation for selected years (focusing on the next few decades), cumulative GHG mitigation over time, results by region, results by individual mitigation option, and a brief overview of key environmental co-effects. The emphasis here is on identifying and quantifying GHG mitigation opportunities at various economic values of GHGs, not on simulating a specific policy.

Mitigation Responses under Various GHG Mitigation Scenarios

This section estimates net GHG emissions from U.S. forestry and agriculture, reported as changes from the baseline levels, through a combination of sequestration and emission reduction strategies. The primary approach evaluated throughout this report is the assignment of a price for GHG emissions and sequestration. Under such pricing, landowners or other economic agents would receive payments for increasing sequestration and reducing emissions and would make payments for increasing emissions or reducing sequestration. The actual mechanism of providing GHG incentives and disincentives for participants specifically is not addressed here. The basic principle in the GHG price analyses below is that GHG prices provide incentives for increasing sequestration through land-use change, forest management, conservation tillage, and other forms of land management, and for decreasing emissions through land-use change (e.g., deforestation), harvesting, input use, and processes that generate non-CO_2 GHGs.

Varying the prices of GHGs in the FASOMGHG model of the forest and agriculture sectors allows for an evaluation of the total GHG mitigation potential from these sectors at different economic incentive (price) levels and identifies the activities and regions that comprise the most cost-effective portfolio of mitigation options. Proposing or designing specific climate mitigation policies for these sectors is beyond the scope of this report. Thus, the section continues with a description of hypothetical core price scenarios for GHG emissions and sequestration. This approach is consistent with numerous modeling efforts conducted in the recent past that have examined GHG mitigation responses across countries, time, and sectors to hypothetical GHG price scenarios.[1] Following the scenarios description, the section presents mitigation results from the FASOMGHG model. Variations on these core price scenarios are presented in subsequent chapters.

Boxes 4-1 and 4-2 detail reporting conventions used throughout the next few chapters with respect to measurement units and mitigation quantities across time periods.

Scenarios Description: Constant and Rising Incentives for GHG Mitigation

The mitigation analysis begins by stipulating a core set of scenarios that simulate the effects of setting a value for GHGs and modeling the subsequent effect on economic behavior and GHG emissions and sequestration.

Constant-Price Scenarios

The core price scenarios are described in Table 4-1 and are divided into two groups. The first group includes the constant-price scenarios, which evaluate GHG price levels ranging from $1 to $50 per tonne of CO_2 equivalent (t CO_2 Eq.) but assumes that the prices remain constant in real (inflation-adjusted) terms over time. Because many climate-modeling analyses use carbon (C), rather than CO_2, as the unit of measure, Table 4-2 presents the carbon price equivalent to the CO_2 prices. The purpose of evaluating a range of GHG prices is to see not only how the total level of mitigation changes over the price range, but how the composition by activity and region changes as well.

Box 4-1: Measurement Units Reported in the Analysis

- The units of exchange for all GHGs are tonnes (t) of CO_2 equivalent (Eq.): 1 tonne (metric ton) = 1,000 kg = 1 Megagram (Mg) = 1.102 short tons = 2,205 lbs.
- CH_4 and N_2O are converted to CO_2 Eq. with GWPs from the IPCC (1996) Second Assessment Report (see Box 1-1 in Chapter 1).
- Most mitigation results in this and subsequent chapters are given in teragrams (Tg) of CO_2 Eq. 1 Teragram = 1 million tonnes.

[1] For a sample of modeling efforts evaluating the effects of broad GHG incentive analyses, consult Web sites for the Stanford Energy Modeling Forum (EMF) (http://www.stanford. edu/group/EMF/publications/index.htm), the MIT Joint Program on the Science and Policy of Climate Change (http://web.mit.edu/globalchange/www/reports.html), and The Pew Center for Global Climate Change (http://www. pewclimate.org/policy_center/reports/) among others.

Box 4-2: Methods Used for Reporting GHG Mitigation Results at Different Points in Time

Annual averages: Present the average level of GHG reductions represented in FASOMGHG for a given year. For the purposes of this report, the annual values for 3 specific years—2015, 2025, and 2055—are used to represent results in the short, intermediate, and long runs. These years represent the midpoint of the decades 2010, 2020, and 2050 tracked in the model and are annual averages for the decades.

Cumulative: Reports results as the cumulative GHG mitigated over the full projection period or period specified. This value is the amount of GHG mitigated in year n plus the total amount mitigated in year (n – 1) + (n – 2) + (n – 3) ... back to the beginning year of the simulation (2010). Although specific options may increase emissions compared to the baseline, the cumulative effect may still be a net GHG reduction as a result of the reductions from the full suite of mitigation options.

Annualized quantities: Because mitigation effects can vary tremendously over time, a concise summary metric is needed to convey the GHG mitigation potential over a given time period. The metric used for these purposes in this report is the annualized equivalent value GHG mitigation quantity. The annualized equivalent refers to the equivalency between the *net present value* of all GHG mitigation over a given projection period (typically the full horizon, 2010 to 2110, but shorter time horizons can be considered)—accounting for variable GHG gains and losses over time—and receiving a fixed quantity of GHG mitigation each year for the same projection period. By using net present value concepts, the annual GHG effects are time discounted; therefore, near-term effects are weighted more heavily than those in later time periods. (The rationale for such an approach is discussed in Herzog et al. [2003].) The discount rate used is 4 percent per year. More information on this metric is provided in Box 4-5.

Table 4-1: Core Price Scenarios

	Initial Price in 2010 ($/t CO_2 Eq.)	Annual Price Growth	Price Cap
Constant Prices			
	$1	0	None
	$5	0	None
	$15	0	None
	$30	0	None
	$50	0	None
Rising Prices			
	$3	1.5%/yr	None
	$3	4%/yr	$30
	$20	$1.30/yr	$75

Table 4-2: CO_2 and C Price Equivalents

CO_2 Price ($ per t CO_2 Eq.)	C Price ($ per t C Eq.)
$1	$3.67
$3	$11.01
$5	$18.35
$15	$55.05
$20	$73.40
$30	$110.10
$50	$183.50
$75	$275.25

Note: One unit of C equates to 3.67 units of CO_2.

Rising-Price Scenarios

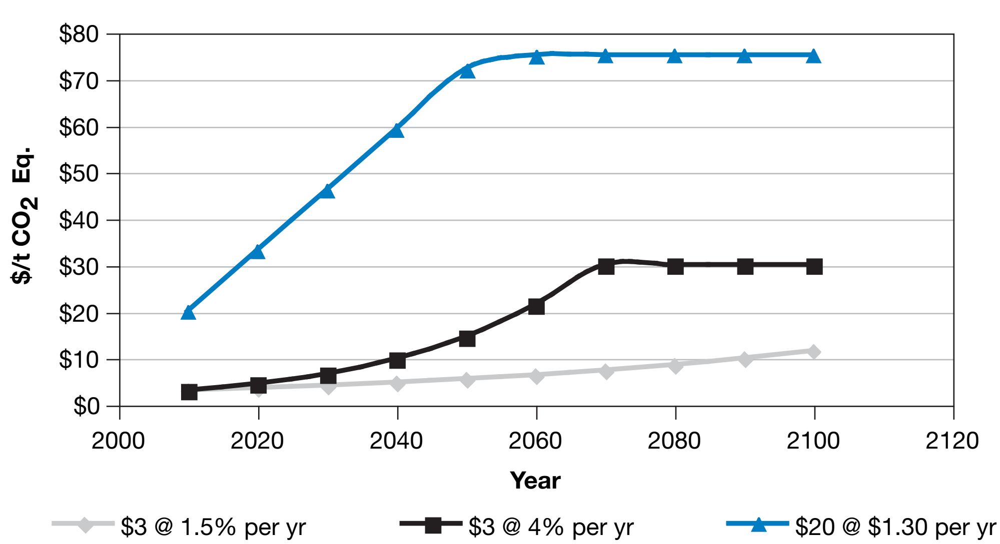
The second group of scenarios in Table 4-1 addresses rising GHG prices, wherein an initial price is asserted beginning in Year 2010, as well as a rate of increase over time. These scenarios provide a means to examine whether the incentive for delayed action to capture mitigation at higher future prices is quantitatively important in these sectors. Figure 4-1 shows the price trajectories associated with each of the three rising-price scenarios, illuminating the differences in the rate of increase and price levels attained.

The first two rising-price scenarios have a modest initial price of \$3/t CO_2 Eq., rising alternatively at 1.5 and 4 percent per annum over the time period. The price caps out at \$30/t CO_2 Eq. under the 4 percent price rise scenario. The third scenario commences at a price of \$20/t CO_2 Eq., rising at \$1.30 per year, capping out at a price of \$75. This third price scenario roughly matches a fairly aggressive price path considered by modeling efforts tied to the Stanford University EMF (http://www.stanford.edu/group/ EMF/home/index.htm). Price caps are introduced to keep carbon prices from reaching seemingly unrealistic levels and are in accordance with other scenarios tested in past research. For further discussion of rising price scenarios, see van't Veld and Plantinga (2005).

The model is initially run to reflect comprehensive coverage. Comprehensive means that all forestry and agricultural activities and all GHGs (CO_2, CH_4, N_2O) represented in FASOMGHG are subject to the GHG payment scenarios. These results, in essence, help identify the *competitive potential* of individual mitigation options and of the aggregate U.S. forest and agriculture sectors for GHG mitigation. See Box 4-3 for a description of technical, economic, and competitive potential as they relate to assessing GHG mitigation. Later, the report considers a more refined set of scenarios that are less comprehensive and more selective in coverage.

The FASOMGHG model is run in decadal time steps for the time period 2010 to 2110. Because there is greater uncertainty in model projections beyond the first several decades, the analysis results focus primarily on selected years: 2015, 2025, and 2055. Longer-term results are presented to highlight the unique temporal dynamics of carbon sequestration mitigation strategies in the forest and agriculture sectors. The following discussion focuses first on mitigation results for the constant-price scenarios and then turns to results for the rising-price scenarios.

Figure 4 1: Price Trajectories for Rising Price Scenarios



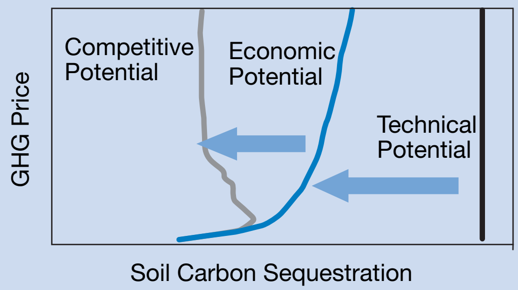
Mitigation Response to Constant GHG Price Scenarios

The mitigation responses to the constant GHG price scenarios are presented in the following order:

- land-use and land management effects,
- total national GHG mitigation quantities for selected years,
- total cumulative GHG mitigation over time,
- GHG mitigation by individual forestry and agricultural activities,
- GHG mitigation by region, and
- non-GHG environmental co-effects.

Box 4-3: Technical, Economic, and Competitive Potential of a GHG Mitigation Option

Example: U.S. agricultural soil carbon sequestration potential



Source: McCarl and Schneider (2001).

The *technical* potential reflects the maximum biophysical potential for GHG mitigation if all resources were committed to this objective without regard to cost. The *economic* potential incorporates the cost of mitigation options by showing that increasing levels of compensation are necessary to procure higher levels of GHG mitigation from the activity. The economic potential can fall well within the technical potential at price ranges considered in this analysis. Finally, the *competitive* potential reflects the interaction of the GHG mitigation activity with all other activity in the forest and agriculture sectors.

For example, while the economic potential shows that agricultural soil carbon sequestration becomes more profitable at higher prices, the competitive potential recognizes that other mitigation options within the sectors (such as afforestation and biofuels) also become more profitable at higher prices. Therefore, some of the economic potential for agricultural soil carbon sequestration is diverted to other more profitable options within forestry and agriculture at higher GHG prices.

A summary of the results that unfold under the constant-price scenarios is presented in Box 4-4.

Land-Use and Land Management Effects

The GHG price incentives alter the economic returns to land and can thereby affect the way that land is allocated across uses. Figure 4-2 illustrates this by showing differences in land use in Year 2025 simulated by variations in the GHG price.

The largest impact is on private timberland, which increases from 315 million acres (128 million ha) in the baseline ($0 price) to about 427 million acres (173 million ha) at the $50/t CO_2 Eq. price, reflecting the prominent role of afforestation in the higher price scenarios. The gain in timberland comes at the expense of losses in both cropland and pastureland. However, this gain in timberland may be temporary. As shown in Figure 4-3, the large increase in timberland at the beginning of the period brought about by a high GHG price ($50/t CO_2 Eq.) dissipates over time as the total

Box 4-4: Summary of Constant GHG Price Scenario Results

The mitigation responses to the constant GHG price scenarios are summarized here and presented in detail in the main text and in Table 4.A.1 in the appendix:

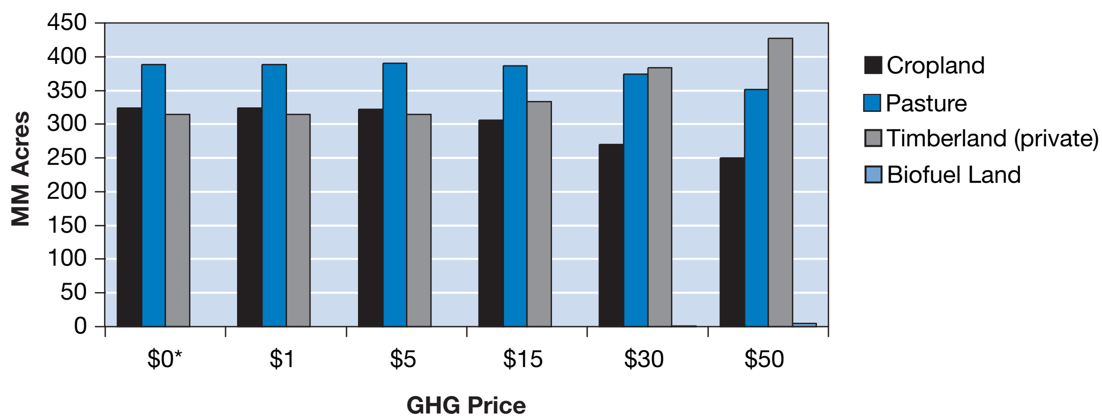
- The lower GHG prices have little effect on land-use change. Starting at the $15/t CO_2 Eq. (or $55/t C Eq.) price, however, appreciable effects on cropland (decline) and timberland (increase) start to materialize. It is not until the highest prices that pastureland begins to decline and biofuel lands increase.
- In the first decade, total national GHG mitigation is low at the low GHG prices—121 Tg CO_2 Eq./year (or 33 Tg C Eq.) at the $1 CO_2 price ($4/t C). This would offset about 2 percent of total national GHG emissions. However, under the highest price scenario ($50), 1,500 Tg CO_2, or over 21 percent of the current national GHG emissions total, could be mitigated.
- Forest management and soil carbon sequestration are dominant at the lower GHG prices. At a $5 CO_2 price, these activities account for 86 percent (260 Tg CO_2 Eq., or 71 Tg C Eq.) of total mitigation by 2015.
- Afforestation is the dominant mitigation activity at the higher GHG prices. At $50, 877 and 1,296 Tg CO_2 Eq. (or 239 and 353 Tg C Eq.) are mitigated by 2015 and 2025, respectively.

area of timberland reverts back to baseline levels after several decades. This reversion of lands to baseline conditions is driven by the fact that, at some point, the economic returns from converting lands back to agriculture are higher compared to keeping lands tied up in forestry. Moreover, there continue to be exogenous demands for land to be used for developed uses, which can divert land that otherwise may be allocated to forests. Thus, reversals occur in both land use and accumulated carbon benefits.

In addition to altering the allocation of land uses, GHG prices can also affect how land within a major use is managed. Table 4-3 shows the area of land converted from conventional crop tillage to reduced tillage under the baseline and GHG price scenarios over time.

In the baseline, FASOMGHG projects a fair amount of new reduced tillage by 2015—20 million acres (8 million ha)—and this amount grows over time to more than 30 million acres (12 million ha)

Figure 4 2: Land Use in 2025 at Different GHG Price Levels



*Baseline
Notes: $ represent price per tonne, CO_2 Eq.
Quantities are in million acres.

Figure 4 3: Timberland Area over Time: $50/t CO_2 Eq. vs. Baseline

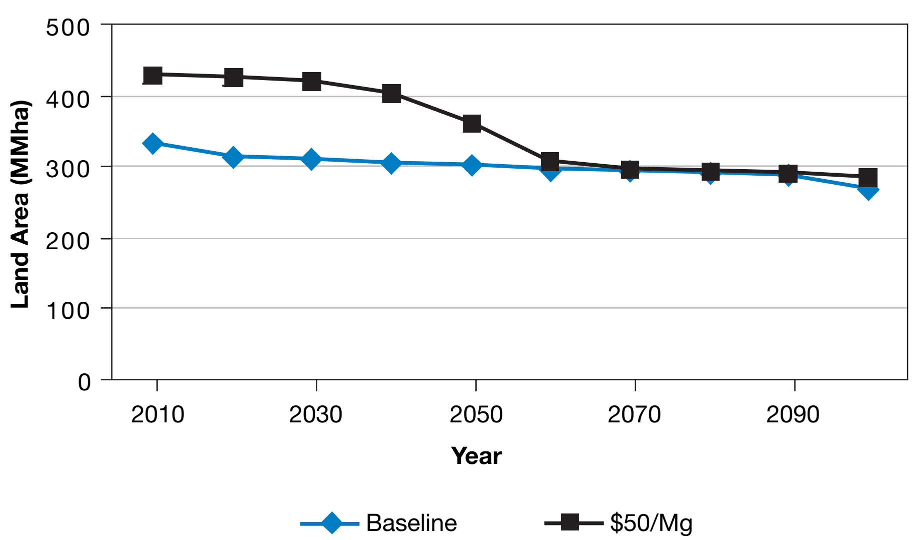


Table 4-3: Acreage Converted from Conventional Tillage to Reduced Tillage under Baseline and GHG Prices: U.S. Total (Million acres)

Year From Conventional Tillage to . . .	Baseline	GHG Price ($/t CO_2, constant over time) $1	$5	$15	$30	$50
	Million Acres[a]					
2015						
Conservation tillage	10.5	48.5	31.4	2.1	0.4	0.6
Zero tillage	9.8	40.6	111.7	153.8	144.6	129.3
Total reduced tillage	20.4	89.2	143.1	155.9	145.0	129.9
2025						
Conservation tillage	20.3	6.4	0.3	0.0	0.1	0.1
Zero tillage	5.4	8.0	4.9	3.2	4.2	3.2
Total reduced tillage	25.7	14.4	5.3	3.2	4.2	3.3
2055						
Conservation tillage	27.5	6.1	0.1	6.2	0.0	0.0
Zero tillage	3.6	6.6	3.1	2.0	3.0	0.4
Total reduced tillage	31.0	12.7	3.2	8.2	3.0	0.4

[a] Baseline acres are the projection of tillage change under no GHG mitigation scenario. Acres for the GHG price scenarios are absolute values, rather than differences from the baseline (note: many other estimates in the report are the latter).

by 2055. However, the amount of cropland converted to reduced tillage rises dramatically under GHG pricing, ranging from about 90 to 155 million acres (36 to 63 million ha) by 2015. The latter number is almost half of the nation's cropland base. Most of this land goes into zero tillage ("no-till") practices. This is especially pronounced at the higher GHG prices, for which the extra financial gain from reducing tillage further is most pronounced. Note that the decline in tillage conversion after 2015 does not mean that reversion to conventional tillage is occurring. Rather, it means that there are fewer acres converting from conventional tillage to conservation or zero tillage at that time, primarily because most of these conversions have already occurred in previous periods.

However, note that the total reduced tillage acreage is highest at the $15 GHG price. Reduced tillage acreage is lower under the $30 and $50 prices because the amount of total cropland is projected to decline as land is diverted from crop production to forests and biofuels at the two higher prices, as shown in Figure 4-2. This relative decline in tillage adoption at the highest prices underscores the differences in economic and competitive potential referenced in Box 4-3.

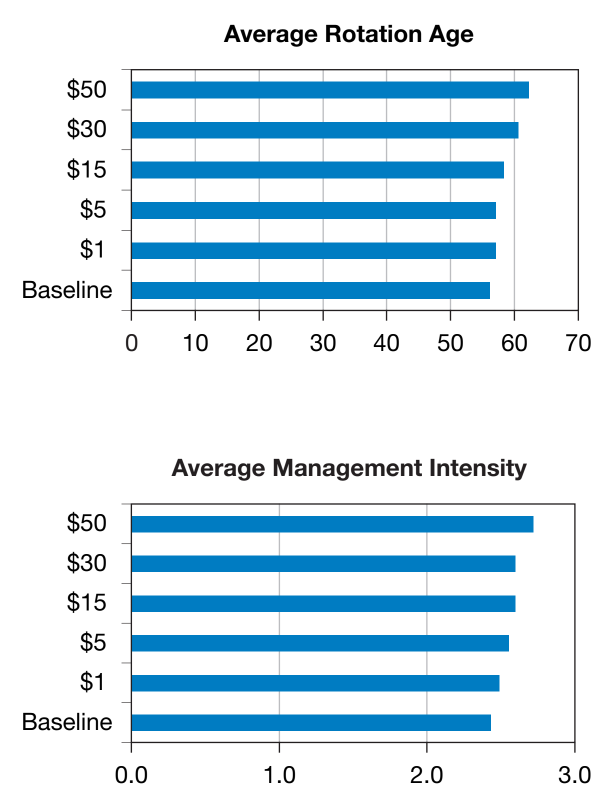
The introduction of GHG prices also induces changes in forest management. Figure 4-4 illustrates the effects of different GHG prices on the average rotation (harvest) age of existing timber stands and the average management intensity of timber stands that are reforested after harvest. Chapter 2 discusses how GHG prices can extend harvest rotation ages; Figure 4-4 gives empirical evidence of this effect. Higher GHG prices tend to lengthen the rotation age, although the effect is not dramatic. The projected baseline (national) average rotation age is about 56 years for the 2015 period. This rises to about 62 years at a price of $50/t CO_2. Management intensity is indexed on a scale of 1 to 4; 4 is the most intensive form of forest management (e.g., site preparation, fertilization, thinning, prescribed burns), and 1 represents essentially no active management. Figure 4-4 shows that GHG prices raise management intensity because the additional management generates additional carbon.

Total National GHG Mitigation Quantities for Selected Years

Figure 4-5 presents total national results for the constant-price scenarios in terms of annual GHG mitigation achieved for the focal years 2015, 2025, and 2055. More detail on the contribution of specific activities to the national mitigation total for these key years can be found in Table 4.A.1 in the appendix to this chapter.

As expected, the total amount of GHGs mitigated by the forest and agriculture sectors rises with the size of the economic incentive. In 2015, annual mitigation totals for the forest and agriculture sectors range from fairly modest at the $1 price (121 Tg CO_2 Eq. per year) to substantial at the $50 price (about 1,500 Tg CO_2 per year). These quantities are, respectively, just under 2 percent and just under 22 percent of 2003 GHG emissions for the United States (EPA 2005), the latter of which could clearly be a substantial contribution to aggregate national mitigation potential, although at that price ($50/t CO_2 Eq. or $183.50/t C Eq.), mitigation options from other sectors could be substantial as well.

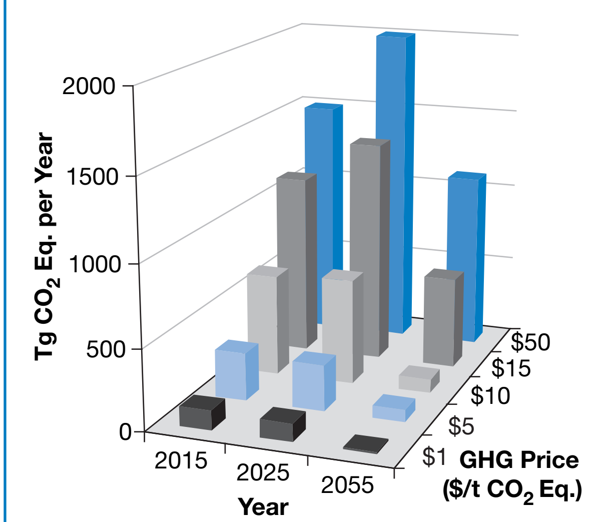
Figure 4 4: Effect of GHG Prices on Forest Management Variables, 2015



Note that the annual mitigation quantities rise between 2015 and 2025, particularly at the higher prices for which forest carbon sequestration from afforestation—which takes some time to culminate—plays a more significant role in the mitigation portfolio, as discussed below. The mitigation potential is generally lower in 2055 than in 2025 or 2015, reflecting the saturating and reversal effects of sequestration options referenced above. More discussion of the time element of mitigation options in these sectors now follows.

Figure 4 5: National GHG Mitigation at Representative Years by Price (2015, 2025, and 2055)

Quantities are in Tg CO_2 Eq. per year net emissions reduction below baseline.

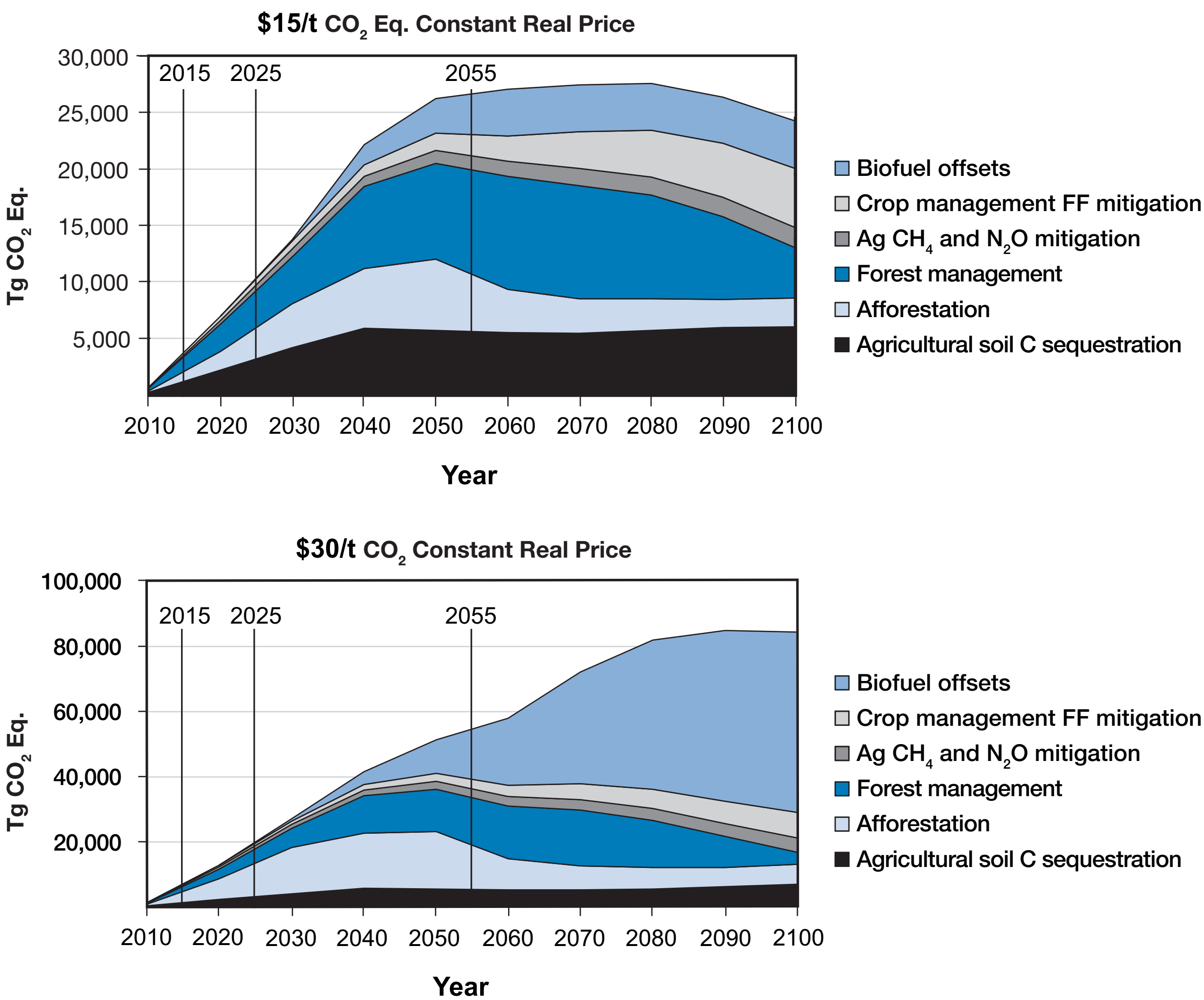


Total Cumulative GHG Mitigation Over Time

Given the unique dynamics of carbon sequestration, it is especially important to look at cumulative GHG mitigation results over time. In a given year, a specific mitigation option can produce an increase or reduction in GHG emissions relative to the baseline. Reporting the results annually may therefore hide the cumulative effect of the mitigation options over time. The long-term emission reductions and sequestration are more important than short-term fluctuations when addressing climate change issues.

Figure 4-6 shows cumulative GHG effects over the entire projection period for the $15 and $30 per t CO_2 Eq. constant price scenarios, respectively. After several decades, some reversal of carbon sequestration occurs as soil carbon equilibrium points are reached and carbon reversals occur through timber harvesting and reversion of afforested lands back to agriculture. Afforestation efforts early on in the period accumulate for several decades as the newly planted trees sequester carbon. Then, as the trees are harvested in the future, CO_2 is released again into the atmosphere, reversing some of the cumulative carbon built up

Figure 4 6: Cumulative GHG Mitigation over Time
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.



*Note differences in the quantity range on the vertical axis of each diagram.

over time. Cumulative agricultural soil carbon sequestration rises, then stabilizes after several decades as the carbon benefits of reduced tillage practices saturate. Forest management shows a saturating and slight reversal effect as well.

These patterns highlight an important difference between the duration of sequestration relative to other mitigation options within the forest and agriculture sectors. While the sequestration options display saturation and impermanence, the fossil fuel CO_2 and non-CO_2 emission reduction options essentially do not. The latter reductions are considered more permanent, because the avoidance of an emission does not create the same biophysical diminishing returns and risk of re-release as sequestration.[2] Differences between the cumulative contribution of sequestration and nonsequestration options widen over time and are particularly pronounced in the second part of the century and at the higher GHG prices.

GHG Mitigation by Individual Forestry and Agricultural Activities: Annualized Results

One way to summarize the net effects of the differing time dynamics is to determine a single measure of GHG effects over the entire simulation period 2010 to 2110. The measure employed here computes the annualized equivalent GHG quantity effect. By annualizing the estimates, one focuses more on comparing mitigation quantities across activities and regions and focuses less on comparisons across points in time. Box 4-5 describes how the annualization approach is applied to generate GHG mitigation estimates in this study.

[2] The analysis does not explicitly consider that avoiding CO_2 emissions from fossil fuel might also have some elements of impermanence as well. Avoided fossil fuel use simply retains the carbon stock below ground for possible release in the future. Although this is not as volatile and subject to rapid release as terrestrial carbon, there are some risks of impermanence nonetheless. Non-CO_2 emissions avoidance is somewhat less prone to the impermanence effect than CO_2 fossil fuel emissions.

Box 4-5: Annualizing Results over the Projection Period

One way to summarize the net effects of the differing time dynamics is to determine a single measure of GHG effects over the entire simulation period 2010 to 2110. By annualizing the estimates, one can focus more on broadly comparing mitigation quantities across scenarios, activities, and regions and focus less on comparisons across specific points in time.

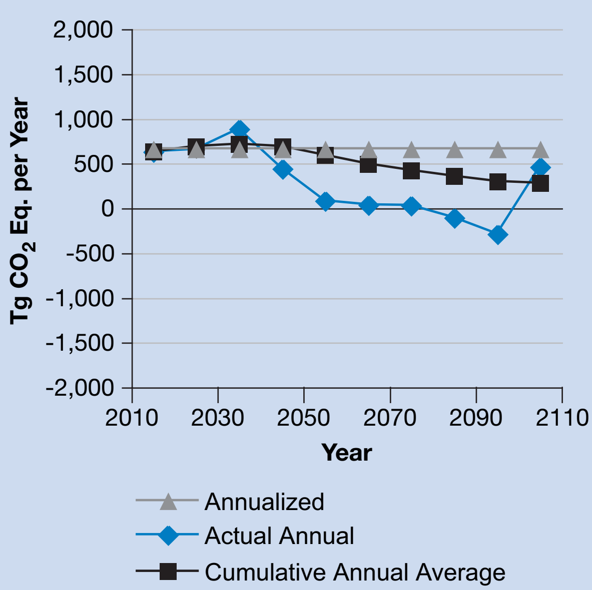
The annualized value provides a single measure that essentially "smoothes out" variability over time, while using the notion of time discounting to enhance the value of near-term mitigation over mitigation occurring in the distant future. Herzog et al. (2003) discuss the rationale for using time-discounting concepts to quantify physical mitigation quantities over time. Note that the annualization approach outlined here is appropriate only when GHG prices are constant over time. Therefore, only the constant-price scenarios in this report are reported using annualized estimates.

The annualized measure is computed by first taking the net present value of the GHG mitigation quantities over time: $NPV_G = \sum_{t=1}^{T} G_t/(1+r)^t$, where G_t is the GHG effect in time period (decade) t; T is the length of the simulation (in this case 100 years); and r is the annual discount rate, which is 4 percent for this analysis. The NPV_G value in the equation above is then annualized via the following calculation: $G_A = NPV_G * AF$, where AF is the annualization factor for converting a lump sum present value, such as NPV_G into its annualized equivalent. For a 100-year time period evaluated at a 4 percent discount rate, the AF is 0.0408. The formula for the annualization factor is $AF = r(1+r)^T / [(1+r)^T-1]$.

Figure 4-7 shows the effect of providing a single annualized value for a highly variable time trend such as the annual mitigation estimates for the \$15/t CO_2 Eq. price scenario. In the figure, the actual projected annual values vary from about +900 Tg CO_2 Eq. per year in the middle of the projection to –300 Tg CO_2 Eq. per year toward the end of the projection, reflecting the carbon reversal pattern discussed earlier in this chapter. The annualized mitigation quantity using the formula referenced above is 667 Tg CO_2 Eq. per year (the flat horizontal line in Figure 4-7). The annualized line can be compared to the third line in Figure 4-7, which is the cumulative annual average over the entire projection period from 2010 to the point in time referenced in the figure. Note that the three annual values (actual, cumulative average, and annualized) are fairly close in value for the first several decades of the projection. Then, as carbon reversal occurs, the actual annual values drop sharply and the cumulative annual estimate drops gradually, while the annualized value, by definition, stays fixed.

Box 4-5: (continued)

Figure 4 7: Comparison of Actual, Cumulative Average, and Annualized GHG Mitigation Value Calculations at \$15/t CO_2 Eq.: 2010 2110



The FASOMGHG model allows projection of scenarios out for 100 years; however, policy time frames are likely to be shorter than that. Indeed the results discussions above have tended to focus on results for the first 40 to 50 years after the mitigation scenario is initiated. This raises the question of whether results should be annualized over time frames shorter than 100 years. The results in Figure 4-7 suggest this could make a difference in quantifying a scenario's GHG benefits. To demonstrate this point, Table 4-4 shows how shortening the time horizon for quantifying GHG effects from 100 years to 50 years and 20 years, respectively, changes the annualized mitigation quantity estimate.

The first column in the table presents annualized quantity estimates for each activity and all activities combined when all projected values over the 100-year projection period (positive and negative) are applied to the annualization formula above. As shown in Figure 4-7, the total quantity is about 667 Tg CO_2 Eq. per year. When the annualization is performed over a 50-year period, all effects after 2060 are ignored. This produces a larger annualized estimate (about 760 Tg) because the future reversal of forest and soil carbon in the latter half of the century is not deducted. Shortening the time horizon to 20 years increases the annualized estimate even further (about 790 Tg), because none of the carbon reversal from afforestation and soil carbon management is included (some was included in the 50-year estimate) and thus only the positive accumulations are taken into account. One factor, though, that diminishes the 20-year estimate relative to the 50-year and 100-year estimates is that the latter two include biofuels, and the first estimate does not. The reason that the 20-year estimate does not include biofuels is that biofuel demand will not be sufficient to induce production for several decades at this price (\$15/tonne) under assumptions maintained in this analysis. The sensitivity of the model results to the biofuel demand assumptions is explored later in this chapter.

In summary, time dynamics are an important part of the GHG mitigation story in forestry and agriculture, and these effects are emphasized in a number of places throughout this report. However, an annualized estimate provides a theoretically consistent approach to capture these dynamic GHG effects in a single measure, thereby allowing for broad comparisons of mitigation quantities across activities, regions, and price scenarios. The annualized estimate depends on the length of time over which the GHG effects are considered (e.g., 20, 50, ... 100 years). For the purposes of this report, the annualized estimates will typically be presented for the 100-year time horizon, because this is the most complete estimate available and does not ignore potentially important reversal effects in the distant future.

Table 4-4: Comparison of Annualized GHG Mitigation Estimates (Tg CO_2 Eq. per year) across Alternative Time Horizons at a GHG Price of \$15/t CO_2 Eq.

	Annualized over ...		
Activity	**100 Years**	**50 Years**	**20 Years**
Afforestation	137.3	164.5	220.0
Forest management	219.1	258.7	244.7
Agricultural soil carbon sequestration	168.0	190.0	243.9
Fossil fuel mitigation from crop production	53.0	46.3	41.6
Agricultural CH_4 and N_2O mitigation	32.0	34.5	38.2
Biofuel offsets	57.2	65.1	0.0
All Strategies	666.7	759.1	788.4

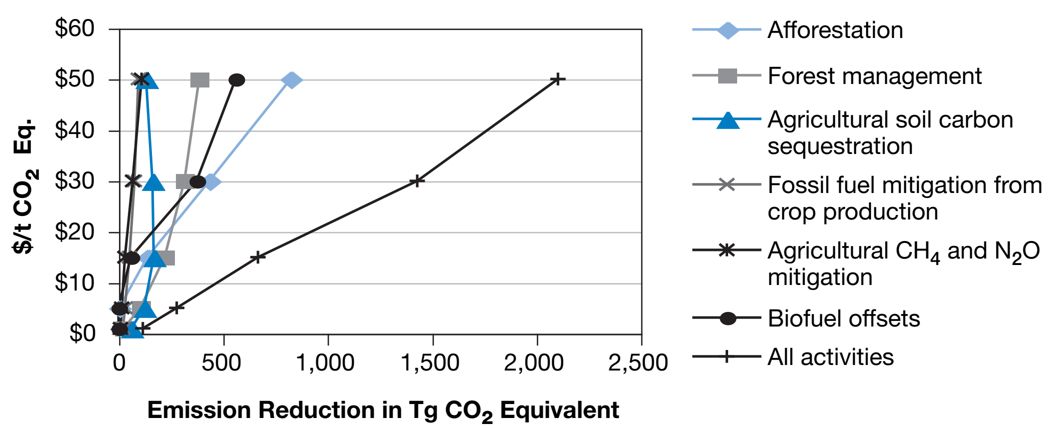
Table 4-5 presents the annualized GHG quantity effects for each major mitigation option by each constant-price scenario. These data constitute a GHG mitigation supply function for U.S. forestry and agriculture, as illustrated in Figure 4-8. The table and figure show that agricultural soil carbon sequestration and forest management are the dominant strategies at low prices, afforestation and biofuels dominate at higher prices, and non-CO_2 gas mitigation in agriculture plays a relatively small role in sector strategies.

Annualized GHG Mitigation by Option. *Afforestation* starts to take hold at the middle price ($15) and becomes the dominant mitigation strategy at the highest prices considered ($30 and $50).[3] This reflects higher opportunity costs of converting agricultural land to forestland than for changes in carbon management practices on forestland and agriculture. It also demonstrates that, once adopted, afforestation can have a larger GHG impact than changes in management within existing uses. Though, as shown above, these effects are quite uneven over time.

Table 4-5: National GHG Mitigation Totals by Activity: Annualized Averages, 2010–2110
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010–2110.

	Constant Prices Over Time				
Activity	**$1**	**$5**	**$15**	**$30**	**$50**
Afforestation	0.0	2.3	137.3	434.8	823.2
Forest management	24.8	105.1	219.1	314.2	384.8
Agricultural soil carbon sequestration	62.0	122.7	168.0	162.4	130.6
Fossil fuel mitigation from crop production	20.5	31.9	53.1	77.6	95.7
Agricultural CH_4 and N_2O mitigation	9.4	15.2	32.0	66.8	110.2
Biofuel offsets	0.0	0.1	57.2	374.6	560.9
All Activities	116.8	277.3	666.7	1,430.4	2,105.4

Figure 4 8: GHG Mitigation Supply Function from National GHG Mitigation Totals by Activity
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



[3] The dominance of afforestation as a strategy is tempered somewhat by exogenous restrictions put on the aggregate contribution of biofuel offsets from the forest and agriculture sectors to reflect current projections of potential biofuel demand by the United States (Haq 2002). The effects of relaxing these biofuel demand restrictions are considered below.

Forest management produces results much like afforestation: fairly small amounts of GHG are sequestered at the lower prices, and larger amounts are only realized at the higher prices. Although the amount of GHG mitigation at the lower prices is small, forest management is second only to agricultural soil carbon in terms of mitigation potential at the two lowest prices.

Agricultural soil carbon sequestration and forest management are the dominant strategies at the lower end of the GHG price range ($1 and $5 per t CO_2). This reflects the relatively low opportunity cost associated with adopting reduced tillage or altering forest management practices to sequester more carbon in some places within the country. These actions can produce results fairly early on.

The increase in other mitigation opportunities actually leads to a slight decline in mitigation through agricultural soil carbon sequestration when moving from the $30 to $50 GHG price. This is because land is being bid away from cropland at these higher GHG prices; therefore, the land base on which to modify tillage practice declines.

Fossil fuel mitigation in crop production plays a very small role in total GHG mitigation at the lower prices, increasing contributions at the higher prices. However, even at the highest price scenario, this activity accounts for less than 3 percent of total mitigation in the first 2 decades.

Agricultural CH_4 and N_2O mitigation. Agricultural non-CO_2 gases are a substantial contributor to the agricultural-sector baseline GHG emissions, as shown in Chapters 2 and 3. However, the non-CO_2 mitigation options provide somewhat limited mitigation potential relative to the CO_2 mitigation and sequestration options.

The activities associated with non-CO_2 gas reductions, such as enteric fermentation, manure management, and soil management, make their largest relative contribution to aggregate mitigation at the lowest price evaluated ($1), where they account for 8 percent of the mitigation portfolio. The share drops to about 5 percent of the portfolio at the $5 price and remains at about 5 percent of total mitigation for all prices above that.

One reason that mitigation potential for the non-CO_2 options is so limited in aggregate terms may be the limited amount of data and other information known about the biophysical and economic consequences of these mitigation options (DeAngelo et al. in press). Another factor may be that what is known about some of the non-CO_2 mitigation options shows that they are profitable under BAU conditions and are thereby incorporated into baseline practices, leaving fewer options available for mitigation beyond the baseline. In either case, more data and research may be needed to better gauge the opportunities for non-CO_2 mitigation options in agriculture.

Biofuels are projected to play a substantially larger role in the mitigation portfolio at higher GHG prices and in later decades. Biofuel results are predicted to increase more than tenfold from 2025 to 2055 (see Table 4.A.1 in the appendix).

Several factors contribute to the incidence and timing of biofuel's role in the mitigation portfolio. First, biofuels are largely uneconomic in the baseline and would take a subsidy to become economically competitive with other fuel sources. A GHG price can serve, essentially, as such a subsidy. As the incentive grows, so does biofuel production. But as explained in Chapter 3, the FASOMGHG model imposes exogenous limits on biofuel demand capacity for several decades. As these limits become less binding over time, adoption increases significantly as well.

Biofuels also do not possess the same reversibility effects as its main competing activities at the high GHG prices. Whereas afforested lands are shown to revert back to agriculture after several decades, biofuel effects are more permanent, both in terms of their ability to offset fossil fuel emissions in the first place and their avoidance of future releases of stored carbon through land-use change or practice reversion.

Sensitivity of National-Level Results to Two Key Assumptions. As discussed in Chapter 3, the FASOMGHG model depends on a wide range of data, parameters, and other assumptions that determine the validity of the model simulations. Of these factors, two stand out as particularly worthy of further scrutiny: (1) the assumed time it takes for a change in agricultural soil tillage practices to achieve a new soil carbon equilibrium (i.e., achieve its "saturation" point) and (2) the assumed rate of market penetration for biofuel demand. Boxes 4-6 and 4-7 present a sensitivity analysis of FASOMGHG model results to changes in these assumptions and finds that the national-level results by activity are moderately affected by changes in the assumed time to achieve the new agricultural soil carbon equilibrium point and the time profile of biofuel demand.

Box 4-6: Sensitivity Analysis of Key Assumption: Time to Reach Soil Carbon Equilibrium ("Saturation")

The FASOMGHG model results for agricultural soil carbon sequestration could depend critically on the assumed time period for soil carbon to reequilibrate to a steady state (or "saturate" as described above) following a change in tillage practice. In FASOMGHG, the annual soil increment following a change in tillage practices is calculated as follows:

$$\Delta Ct = (C_{SSR} - C_{SSC})/T_S \qquad [4.1]$$

where ΔC_t is the estimated annual change in year t; C_{SSR} and C_{SSC} are the soil carbon steady-state values under reduced tillage and conventional tillage, respectively; and T_S is the time to steady state (equilibrium). The carbon steady-state values are given by simulations of the CENTURY model (Parton 1996), but CENTURY does not simulate the T_S variable. Therefore, an assumed value for T_S is needed. Note that ΔCt goes to zero once the new steady state is reached. Therefore, both the size and timing of the annual carbon increment are affected by the assumed length of time to reach the new equilibrium.

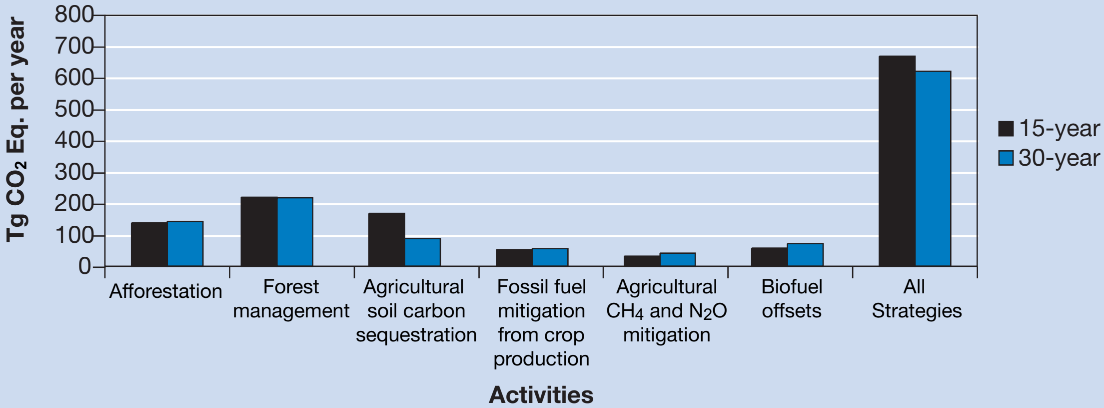
The maintained assumption for the model simulations thus far is that the soil carbon saturation period is 15 years, based on work by West and Post (2002). They quantitatively synthesized the published results of 276 paired treatments of changes in tillage practices from 67 study sites and estimated that the new soil carbon steady state was reached in 10 to 15 years. However, other research has suggested possibly longer saturation periods for tillage change (Lal et al. 1998). To evaluate the sensitivity of the foregoing results to this assumption, the FASOMGHG model was run with an assumed time to equilibrium of 30 years and compared to the results with the 15-year saturation period.

The simulation was run for a constant GHG price of $15, which was selected because all of the mitigation activities come into play at that price. The results in Figure 4-9 are annualized national mitigation estimates for the projection period 2010 to 2110. The annualized contribution of the agricultural soil carbon mitigation declines by almost half, from about 170 Tg CO_2 per year to 90 Tg per year, which is about what one might expect when the time to equilibrium is doubled, and therefore the annual increment calculation in equation [4.1] is halved (assuming the same quantity of mitigation). However, that is not the end of the story. The figure illustrates that not only is there the expected reduction in annual mitigation from agricultural soil carbon sequestration when the saturation period is elongated, but also the contribution of other activities is affected as well. In particular, the reduction in agricultural soil carbon mitigation is partly offset by increased mitigation from biofuel offsets and agricultural CH_4 and N_2O mitigation and to a lesser extent forest carbon and fossil fuel mitigation. The net reduction in mitigation across all activities is under 50 Tg CO_2 per year, so the initial 80 Tg reduction from soil carbon is offset by about a 30 Tg net increase in the other activities. In essence, this shows that GHG mitigation options compete with each other on a fixed land base. When one option becomes less advantageous, the competing options can take up some of the slack.

Box 4-6: (continued)

Figure 4 9: Model Sensitivity to Saturation Period toward a New Soil Carbon Equilibrium from Tillage Change: GHG Price = $15/t CO_2 Eq.

Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



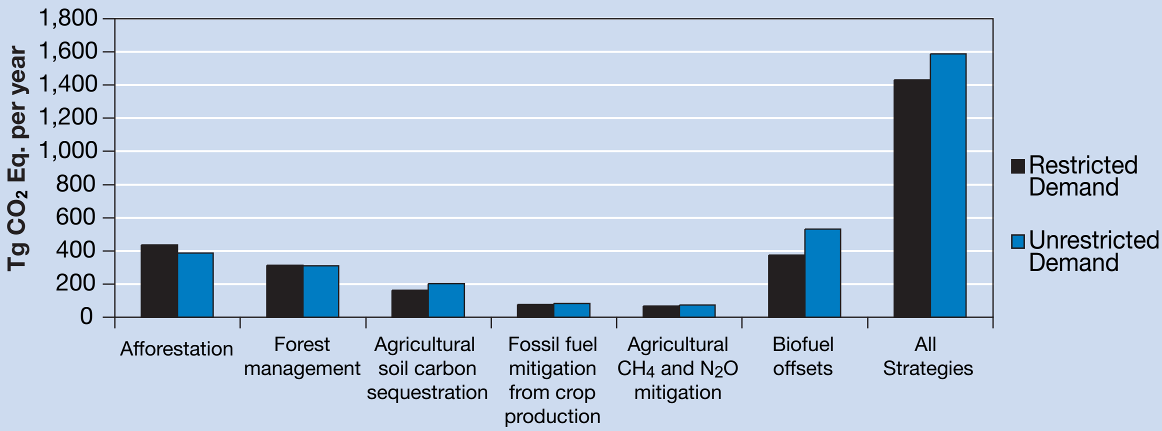
Box 4-7: Sensitivity Analysis of Key Assumption: Biofuel Demand

The FASOMGHG model was modified in this report to confine biofuel production to fall within the capacity limits projected by the EIA's energy forecasts (Haq 2002). As such, some biofuel mitigation that may initially seem profitable within FASOMGHG is excluded for consistency with the EIA estimates. To test for the sensitivity of this assumption, the model was re-run to relax the EIA demand assumption and rely purely on the profitability of biofuel production as a determinant of total biofuels supplied to the market.

The results of this simulation are illustrated in Figure 4-10. The simulation was run at a GHG price of $30/t CO_2 Eq. (constant), which is the price at which biofuels become a substantial contributor to national mitigation totals. Relaxing the biofuel demand restriction raises the contribution of that activity for sensitivity analysis from 375 to 530 Tg CO_2 Eq. per year, more than a 40 percent increase. As with the agricultural soil carbon example, we must consider offsetting effects from the other activities, but they are not all negative. The contribution of afforestation declines as part of the mitigation portfolio, but the contribution of agricultural soil carbon and non-CO_2 mitigation rises, indicating there are complementarities between biofuel production and mitigation from these activities. Notably, land that is diverted from traditional crops to biofuel production tends to sequester more carbon and release less N_2O and CH_4.

Figure 4 10: Sensitivity of Model Results to Assumed Biofuel Demand Restrictions: GHG Price = $30/t CO_2 Eq.

Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



GHG Mitigation by Region

Because the U.S. landscape is quite heterogeneous, the adoption and effectiveness of GHG-mitigating activities will not be uniform across regions within the country. The regional definitions used in this section can be found in Table 3-2 in Chapter 3.

The regional totals distribution at the middle three constant-price scenarios ($5, $15, and $30/t CO_2 Eq.) are illustrated in Figure 4-11. This figure and the corresponding table (Table 4.A.2 in the appendix) with activity detail provide a summary of annualized GHG mitigation quantities by major region, activity, and price scenario. Table 4.A.3 in the appendix reports the regional breakdown of annualized mitigation totals by all key activities modeled.

By and large, the regions with the highest GHG mitigation are the South-Central, Corn Belt, and Southeast regions. At the lower GHG prices, the Lake States and Great Plains are key contributors as well. The contributions of the Corn Belt, Lake States, and Great Plains are primarily in the form of agricultural soil carbon sequestration, whereas the South-Central and Southeast regions are primarily suppliers of carbon sequestration from afforestation and forest management.

The Rockies, Southwest, and Pacific coast states generate relatively small shares of the national mitigation total under all of the price scenarios. From those regions, only forest management from the PNWW produces appreciable mitigation. This is because climate and topography significantly limit the movement of land between major uses such as forestry and agriculture in the western regions.

When biofuel production is selected at the higher GHG prices, this occurs primarily in the Northeast, South, Corn Belt, and Lake States.

Figure 4 11: Total Forest and Agriculture GHG Mitigation by Region
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.

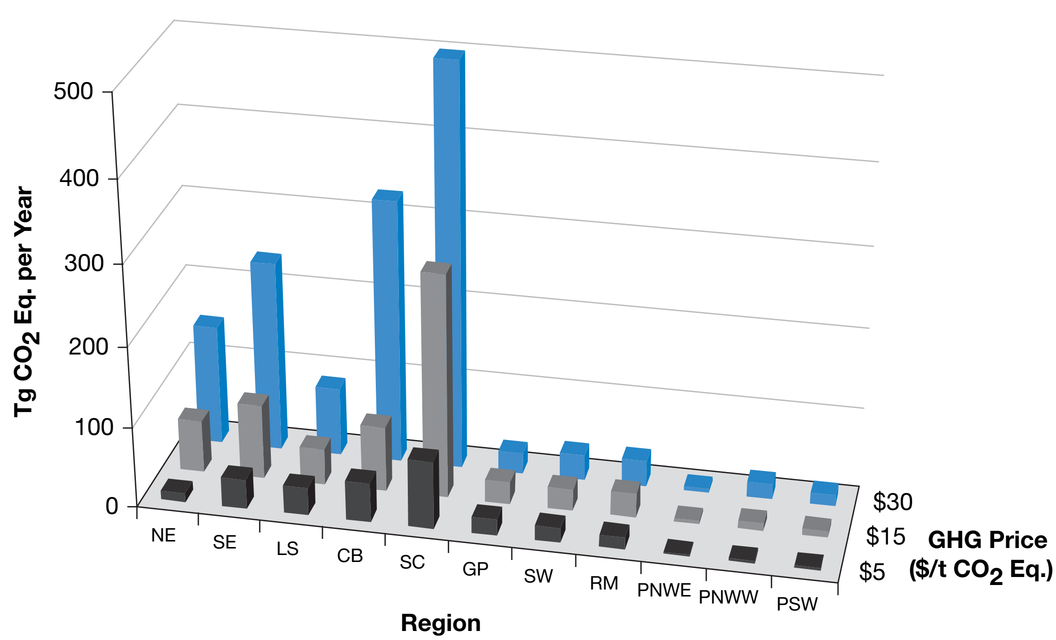


Table 4-6 presents a top 10 ranking of region–activity combinations producing the most GHG mitigation by price scenario. This table illustrates how the distribution of GHG mitigation opportunities varies across regions and activities as the GHG price changes. At the lowest two prices, the top-ranked combination is forest management in the South-Central region, followed by agricultural soil carbon sequestration in the Corn Belt and Lake States. As prices rise, so do the opportunities for afforestation in the South-Central and Corn Belt regions and biofuel production in the Corn Belt, South, and Northeast.

Non-GHG Environmental Co-effects

The undertaking of GHG mitigation activities and the resultant shift of land uses and management practices have the potential to produce environmental co-effects other than climate change mitigation. For instance, the changes in agricultural practices can have an effect on the farm inputs applied, which in turn can affect the loadings of nutrients, erosion, and other residuals into waterbodies.

Table 4-6: Top 10 Region-Activity Mitigation Combinations
Ranks are based on mitigation quantities annualized over the period 2010–2110.

		GHG Constant Price Scenario ($/t CO_2 Eq.)				
Region	**Activities**	**$1**	**$5**	**$15**	**$30**	**$50**
SC	Forest management	1	1	1	3	3
CB	Agricultural soil carbon sequestration	2	2	4	7	10
LS	Agricultural soil carbon sequestration	3	3	6		
GP	Agricultural soil carbon sequestration	4	5	7		
SW	Fossil fuel mitigation from crop production	5	7			
RM	Agricultural soil carbon sequestration	6	8			
SC	Fossil fuel mitigation from crop production	7	6	8	10	
NE	Agricultural soil carbon sequestration	8	9			
CB	Fossil fuel mitigation from crop production	9	10			
CB	Agricultural CH_4 and N_2O mitigation	10				
SE	Forest management		4	3	6	8
SC	Afforestation			2	1	2
NE	Biofuel offsets			5	4	5
RM	Afforestation			9		
SW	Agricultural soil carbon sequestration			10		
CB	Afforestation				2	1
SE	Biofuel offsets				5	4
SC	Biofuel offsets				8	6
CB	Biofuel offsets				9	7
LS	Afforestation					9

To briefly assess these effects, the analysis focuses on a single GHG price ($15/t CO_2 Eq.), as shown in Figure 4-12. Three of the four pollutants reveal a reduction in overall loadings relative to baseline amounts. Phosphorous and erosion loadings reveal the largest reduction of approximately 40 percent each. This reduction in pollutant loadings is tied to the widespread adoption of conservation or zero tillage practices, which reduces erosion and phosphorous runoff that often adheres to soil particles.[4] Over time, however, these loadings return closer to baseline levels. Pesticides are the only loadings that exceed baseline loadings in some cases. This finding reflects the fact that adopting no-till farming practices often requires increased pesticide applications, as chemical means of weed control replace mechanical means.

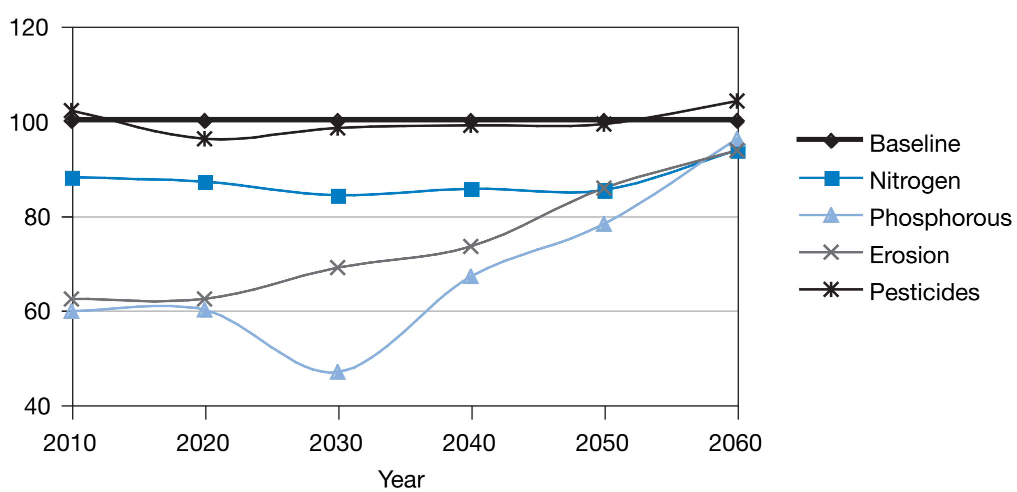
Chapter 7 expands the discussion of environmental co-benefits by evaluating the full range of constant GHG prices, evaluating the net likely impact of these loadings patterns on water quality and considering other environmental co-effects such as biodiversity.

Mitigation Response to Rising GHG Price Scenarios

Up to this point, the chapter has focused on results for the constant GHG price scenarios. Now results from the rising-price scenarios are discussed. The focus of the discussion is primarily on the differences from the constant-price results. A detailed table of mitigation results by activity in key years for the rising-price scenarios is presented in the appendix to this chapter (Table 4.A.4).

As with the constant-price scenarios, there is a larger amount of GHG mitigation with the higher rising-price scenarios; however, the major difference between the constant- and rising-price scenarios is the timing of the mitigation. These timing effects are illustrated in Figure 4-13. As shown earlier, the GHG mitigation totals start high in 2015 and then decline by 2055 under the constant-price scenarios. The rising-price scenarios, however, tend to show the opposite effect. Mitigation is minimal in the early years when prices are low but rises substantially in the later years as the prices escalate for two of the

Figure 4 12: Pollutant Loading Effects Over Time of a $15/t CO_2 Eq. GHG Price



Note: All values indexed to a baseline value of 100.

[4] Recall from Table 4-3 that the $15 carbon price in the year 2015 resulted in the largest conversion of conventional till to either conservation or zero tillage practices.

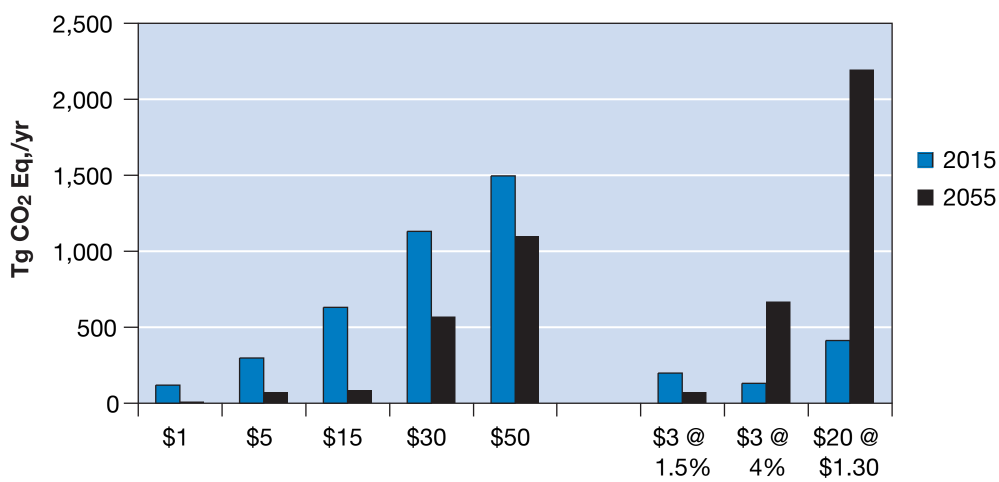
three scenarios. To a large extent, this time pattern of mitigation is the result of the producers of GHG mitigation holding out for the higher prices that occur in the later years of the projection. This is particularly crucial with mitigation options because carbon sequestered early on cannot be re-sequestered in the future. When prices are expected to rise, this provides an incentive to wait on enacting sequestration activity.

Figure 4-14 illustrates cumulative GHG effects over time for the two scenarios that have an initial price of $3 and rise at 1.5 percent and 4 percent, respectively. The main differences between the two scenarios are as follows:

- The scenario with the 4 percent rate of increase demonstrates a substantial delay in mitigation activity, as suppliers wait for the much higher prices to come in the future. Once prices near their $30 cap at mid-century, significant action takes hold.
- The level of mitigation ultimately obtained is substantially larger in the 4 percent scenario, primarily because the price gets much higher in the out years. As such, the biofuel option becomes more attractive. The biofuel option also favors later adoption because the demand for biofuels over time reflects the assumption that the capacity for biofuel use in electricity generation is heavily constrained in the short run but could expand substantially in the long run.

Figure 4-15 shows cumulative GHG mitigation for the more aggressive rising-price scenario, starting at $20/t CO_2 Eq. and rising to $75. This case also produces delay in mitigation but includes a much larger quantity of mitigation than the other two scenarios and has a larger role for afforestation because of the higher starting and ending prices. These figures reveal the expected differences resulting from the higher prices, while highlighting the timing effects that are not seen in the constant-price scenarios.

Figure 4 13: Constant Price Scenarios vs. Rising Price Scenarios and GHG Mitigation
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for 2015 and 2055.



Note: All values indexed to a baseline value of 100.

Figure 4 14: Cumulative GHG Mitigation over Time: \$3/t CO_2 Price Rising at Two Rates
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.

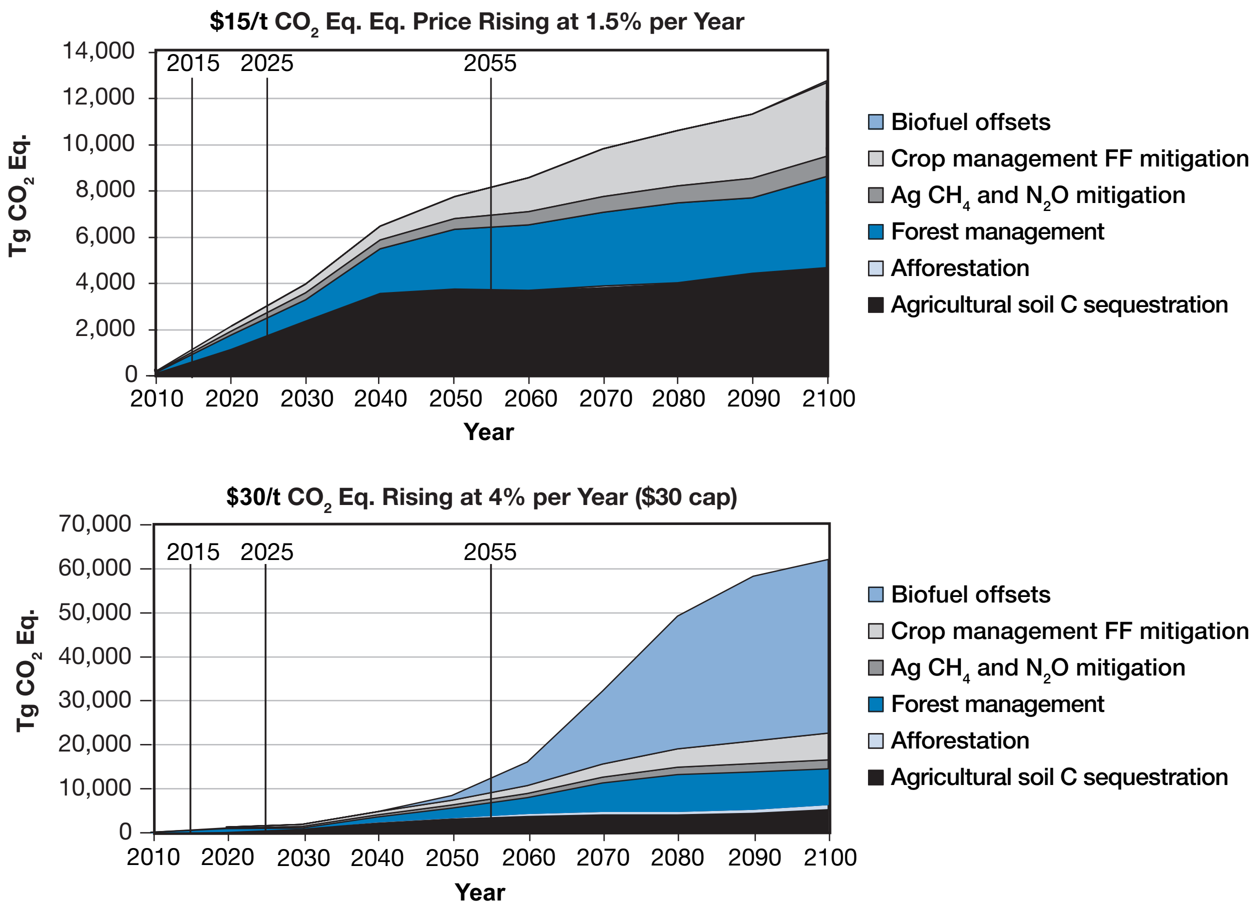
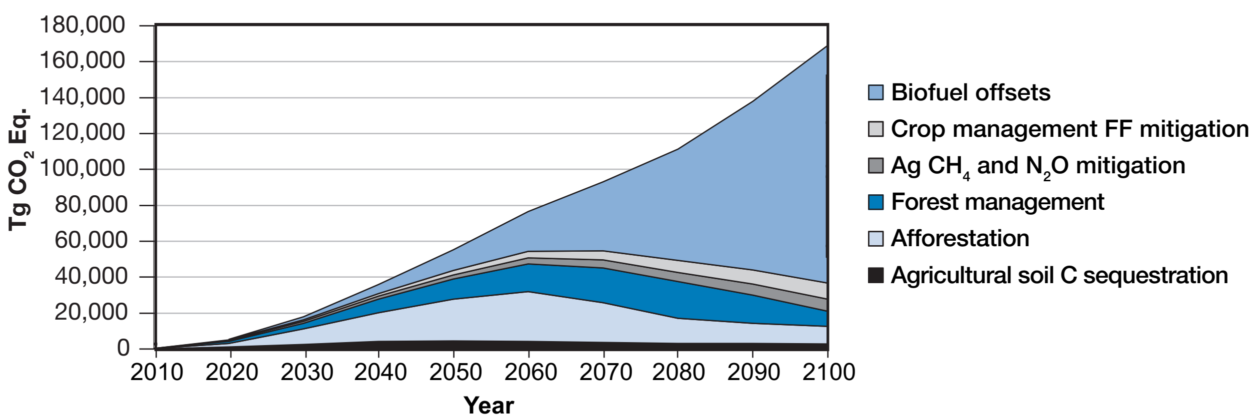


Figure 4 15: Cumulative GHG Mitigation over Time: \$20/t CO_2 Price Rising by \$1.30 per Year (\$75 cap)
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.



Comparison of FASOMGHG Results with Other Analyses

It is useful to compare the results of the analysis presented in this chapter to similar economic studies of GHG mitigation in the U.S. forest and agriculture sectors. It is important to note, however, that this study is rather unique in terms of its depth and breadth of mitigation options covered across the two sectors. In essence, this is a somewhat more comprehensive and integrated assessment of economic potential of the U.S. forest and agriculture sectors together than other studies to date. So a direct and consistent comparison with other studies is not quite possible. However, several studies have looked separately at the national mitigation potential from afforestation, forest management, and agriculture and can thereby provide context for the core results presented above.

Richards and Stokes (2004): Forest Carbon

Richards and Stokes (2004) conducted a thorough review of 36 forest carbon sequestration economic studies throughout the world. Among this group, eight studies estimated marginal cost functions for forest carbon sequestration at the national level for the United States, reportable on an annual basis. Consequently, these eight studies are directly comparable to the results presented in this chapter, once the appropriate adjustments are made to tonnes of CO_2 Eq. per year.[5] Table 4-7 summarizes the range of carbon sequestration quantity and cost results for the eight comparable U.S. studies reviewed by Richards and Stokes and compares them to the results from the constant-price FASOMGHG simulations in this study. The aggregate national forest carbon sequestration estimates in the Richards and Stokes studies ranged from 147 to 2,349 Tg CO_2 Eq./yr at a cost (price) ranging from \$1.36 to \$40.87 per t CO_2 Eq. Most of these studies examine afforestation only or do not break out afforestation from forest management. Only one of the studies presents results for forest management activities, and that study produced an estimate of roughly 400 Tg CO_2 Eq./yr of sequestration at a cost ranging from \$1.63 to 12.81/t CO_2 Eq.

Many compounding factors cause the results to vary widely in the studies reviewed by Richards and Stokes, including but not limited to the extent of ecosystem components included in the carbon calculations, the biophysical foundation for the

Table 4-7: Comparison of FASOMGHG Results in this Chapter to Range of Estimates from Richards and Stokes' (2004) Review Study

	Carbon Sequestration (Tg CO_2 Eq. per Year)				
	This Study: Comprehensive Activities, Annualized Over 2010–2110				Richard and Stokes: U.S.-Based Studies
	GHG Price Scenario (\$/t CO_2 Eq.)				GHG Price Range (\$/t CO_2 Eq.)
Activity	**\$5**	**\$15**	**\$30**	**\$50**	**\$1.36 – \$40.87**
Afforestation	2.3	137	435	823	147 – 2,349
Forest management	105	219	314	385	404[a]
Total forest carbon	107	356	749	1,208	551 – 2,753

[a] Only one study covering the United States included estimates for forest management.

[5] The eight comparable studies are Moulton and Richards (1990), Adams et al. (1993), Parks and Hardie (1995), Callaway and McCarl (1996), Alig et al. (1997), Richards (1997), Adams et al. (1999), and Stavins (1999). Unfortunately, Richards and Stokes did not adjust the studies' results to put them in a common year for dollar comparisons.

carbon sequestration rates used, and the land costs included in cost calculations. However, comparing the U.S. forest carbon sequestration estimates generated by the FASOMGHG results earlier in the chapter suggests they fall well within the range of estimates found in the Richards and Stokes review. FASOMGHG mitigation estimates will generally not reach the high end of the estimates found in the Richards and Stokes study, because FASOMGHG employs economic feedback effects (e.g., timber and agricultural price effects) that will temper sequestration responses, in contrast to studies that estimate mitigation cost functions without market feedback effects.

Stavins (1999): Afforestation

For a further comparison of this chapter's results to other studies, we look at research conducted by Stavins (1999) that synthesized the results from several past studies that were directly comparable to the results presented in his work in that they were national (United States) in scale and focused specifically on afforestation. Stavins computes a 95 percent confidence interval on his national marginal cost function for afforestation and shows that other previously published studies (Richards et al. 1993, Adams et al. 1993, and Callaway and McCarl 1996) fall within that interval.

To compare the results from this study to Stavins', several adjustments needed to be made. First, Stavins' results are presented graphically via a marginal cost function. This enabled one to trace the amount of carbon sequestered nationally to a given level of marginal cost per tonne sequestered. Conceptually, this is similar to evaluating the total amount of carbon that can be sequestered at a given GHG price. This enables direct comparison with the FASOMGHG results presented above. However, further adjustment is necessary to compare Stavins' results, which are expressed in short tons of carbon and 1990 dollars, with the results here, which are in tonnes of CO_2 equivalent and 2000 dollars.[6] These adjustments are made and results are compared in Table 4-8 for the $30 and $50 constant-price scenarios, which are the two scenarios in which forest carbon plays the largest role.

The main implication from the comparative results presented in Table 4-8 is that the core scenario analysis in this report suggests a smaller aggregate potential for forest carbon sequestration than that found in the Stavins study. When this study's afforestation carbon potential is compared to Stavins, which is the most relevant comparison, the mitigation quantities are about one-third to one-half of Stavins' estimates. When forest management is added to the totals from this study, the relative quantities are one-half to three-quarters of the Stavins' estimates.

Table 4-8: Comparison of FASOMGHG Results in this Chapter to Stavins' (1999) Study

	Carbon Sequestration (Tg CO_2 Eq. per Year, above baseline, annualized over 100-year time period)	
	GHG Price ($/t CO_2 Eq.)	
	$30	$50
This Study		
Afforestation	435	823
Forest management	314	385
Total forest carbon	749	1,208
Stavins' Central Estimate[a]	1,330	1,660
This Study as % of Stavins'		
Afforestation	33%	49%
Total forest carbon	56%	73%

[a] Adjustments made to convert Stavins' estimates from 1990 dollars per short ton to 2000 dollars per t CO_2 Eq.

[6] Short tons of carbon are converted to tonnes by dividing by 1.102. Tonnes of carbon are converted to tonnes CO_2 by multiplying by 3.667. 1990 dollars are converted to 2000 dollars using the consumer price index (urban consumers) <www.bls.gov/cpi/home.htm>.

Stavins' paper asserts that one might typically expect econometric estimates, like those in his study, to yield smaller mitigation quantities than estimates using optimization methods like the FASOMGHG model, because of the econometric reliance on "revealed preferences" of landowners.

However, while FASOMGHG does not incorporate the revealed behavior of an econometric model, it does capture (unlike the Stavins study) feedbacks from the commodity and land markets that need to be considered when estimating the net effects of large-scale programs. Large-scale movement of land from agriculture to forests will tend to raise agricultural prices and lower timber prices. This provides an incentive for countervailing movements of land from forest to agricultural use. The multimarket equilibrium nature of FASOMGHG captures these feedbacks and slows the afforestation (and sequestration) process accordingly. Ignoring this feedback tends to overstate sequestration potential all else equal, as Stavins acknowledges in his paper.

Sedjo, Sohngen, and Mendelsohn (2001): Forest Carbon

Since the Stavins (1999) study, other forest carbon sequestration studies have been published that are in some ways comparable to those synthesized by Stavins (see, for instance, Adams et al. [1999], Plantinga et al. [1999], Stavins and Newell [2000], Sedjo, Sohngen, and Mendelsohn [SSM] [2001], and Sohngen and Mendelsohn [2003]). Perhaps the most directly comparable of those studies is the SSM 2001 study, which looks at a wide range of price scenarios similar to the constant-price scenarios in this chapter. The one important difference, though, is the SSM results are for all of North America, while these results are for the United States. Nevertheless, U.S. results are by far the dominant component of the North America results in SSM. Table 4-9 compares SSM results at \$50 and \$100 per tonne of carbon (\$13.62 and \$27.25 per t CO_2 Eq.) with the closest points of comparison in this study (\$15 and \$30 per t CO_2 Eq.).[7]

The SSM mitigation estimates are about one-quarter less than the FASOMGHG results under both price levels. While this is somewhat surprising given the larger continental coverage of the SSM study, many modelers would consider a 25 percent variation in such macro-scale results using two different models a reasonably good correspondence. Further examination of the two models' results suggests that the differences are primarily due to the more detailed modeling of land opportunity costs in U.S. agriculture in FASOMGHG. This produces a more elastic afforestation response than the SSM study, which relies on a single inelastic land-use supply function from agriculture.

Table 4-9: Comparison of FASOMGHG Forest Carbon Sequestration Results in this Chapter with Sedjo, Sohngen, and Mendelsohn (2001)
Quantities for both studies are Tg CO_2 Eq. per year, sequestration above baseline, annualized over 100-year time period.

Sedjo, Sohngen, and Mendelsohn (2001) Scenario	Total Forest Carbon Sequestration (Tg CO_2 Eq. per Year)	This Study Scenario	Total Forest Carbon Sequestration (Tg CO_2 Eq. per Year)
\$13.62/t CO_2 Eq. (\$50.00/t C Eq.)	265	\$15/t CO_2 Eq.	356
\$27.25/t CO_2 Eq. (\$100/tC Eq.)	563	\$30/t CO_2 Eq.	749

[7] The direct comparison between this study's results and those of SSM was enabled with data provided by Dr. Sohngen that is not directly presented in one of the paper's tables.

USDA, Economic Research Service (2004): Agricultural Carbon Sequestration

Most recently a report by the USDA ERS was published that examined the economics of sequestering carbon in the agriculture sector (Lewandrowski et al. 2004). That report examines mitigation options in the agriculture sector, including afforestation but excluding forest management and biofuels. The ERS study produced estimates for the amount of carbon that could be sequestered over a 15-year time period given various carbon prices expressed in $/t C. After converting these to $/t CO_2 Eq. the prices range from $2.72 to $34.05 per tonne (see Table 4-10).

These prices are introduced in a model of the U.S. agriculture sector (USMP), which is a spatial market equilibrium model. All mitigation estimated by this model is relative to a baseline generated by the model. The USMP model results are also separated by forest and soil sequestration, allowing for a comparison to the FASOMGHG soil results. At the lowest GHG price, the amount of overall carbon sequestered ranged from 0.4 to 35 Tg CO_2 Eq. per year. The highest price investigated resulted in total sequestration ranging from 237 to 587 Tg CO_2 Eq. per year.

The range of estimates presented in the USDA ERS report is generally lower than the range of estimates generated by FASOMGHG in this study, for a comparable set of activities and time horizon (15 years). These differences can be expected based on the differences in the models and assumptions embedded in the estimates. Note that the FASOMGHG estimates for these price scenarios are lower when we look over time periods longer than 15 years. However, we cannot compare longer time horizon estimates to the ERS study, which takes a static snapshot of a 15-year program.

Recap of Study Comparisons

Although not a comprehensive comparison of the results of this study to the entire spectrum of results in the literature, the comparisons above provide some validation that the results of various components analyzed here are within the (fairly wide) range of mitigation estimates found in similar economic studies. Differences across the studies can be explained in large part by differences in methodology and geographic coverage. Taken together, these comparisons suggest that the FASOMGHG model produces results that, while more comprehensive in its coverage of both forestry and agriculture than most other studies, are consistent with findings on different component parts (afforestation, forest management, and agricultural soil carbon sequestration).

Table 4-10: Comparison of this Study with Lewandrowski et al. (2004) (USDA ERS)

	This Study (Tg CO_2 Eq./yr net emissions reduction below baseline) After 15 years (Yr. 2025)				USDA ERS (Tg CO_2 Eq./yr) Average annual mitigation for 15-year program					
GHG Price ($/t CO_2 Eq.)	**$5**	**$15**	**$30**	**$50**	**$2.72**	**$6.80**	**$13.60**	**$20.40**	**$27.50**	**$34.05**
Afforestation	12	228	806	1,296	0–31	20–140	105–264	145–378	174–460	224–489
Agricultural soil carbon sequestration	149	204	187	153	0.4–4	3–10	3–30	5–48	11–70	13–95
Total	161	432	994	1,449	0.4–35	25–151	108–295	151–426	185–529	237–587

Appendix 4.A

This appendix provides detailed tabular results that are referenced in the main text of this chapter.

Table 4.A.1: Key Results at the National Level by Activity, Time Period, and Constant-Price Scenarios
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for representative years 2015, 2025, and 2055.

		GHG Price (\$/t CO_2 Eq.)				
Year[a]	**Activity**	**\$1**	**\$5**	**\$15**	**\$30**	**\$50**
2015	Afforestation	0	0	145	557	877
	Forest management	27	121	227	271	301
	Agricultural soil carbon sequestration	66	139	194	191	177
	Fossil fuel mitigation from crop production	17	23	35	46	55
	Agricultural CH_4 and N_2O mitigation	11	15	28	48	69
	Biofuel offsets	0	0	0	16	17
	All activities	121	298	629	1,129	1,496
2025	Afforestation	0	12	228	806	1,296
	Forest management	22	89	156	250	309
	Agricultural soil carbon sequestration	67	149	204	187	153
	Fossil fuel mitigation from crop production	14	18	32	49	62
	Agricultural CH_4 and N_2O mitigation	7	17	36	76	119
	Biofuel offsets	0	0	0	21	83
	All activities	110	285	655	1,390	2,021
2055	Afforestation	1	–7	–270	–873	–426
	Forest management	–10	48	171	322	325
	Agricultural soil carbon sequestration	1	–26	–22	–10	–30
	Fossil fuel mitigation from crop production	14	49	62	92	111
	Agricultural CH_4 and N_2O mitigation	7	11	26	52	101
	Biofuel offsets	0	0	121	990	1,021
	All activities	13	74	86	572	1,101

Table 4.A.2: Total Forest and Agricultural GHG Mitigation by Region
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010-2110.

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
NE	10.9	64.7	148.1
SE	36.4	92.6	236.0
LS	34.6	44.8	84.9
CB	49.0	80.8	326.4
SC	83.9	278.1	507.5
GP	20.5	27.3	25.5
SW	18.1	26.7	31.7
RM	15.3	29.8	32.7
PNWE	2.2	4.3	4.8
PNWW	3.2	9.6	19.1
PSW	3.2	8.0	13.8

Table 4.A.3: Forest and Agricultural GHG Mitigation by Activity, Region, and Price Scenario
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010-2110.

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
Afforestation			
CB	2.0	6.6	162.5
LS	0.0	0.0	14.9
PNWE	0.3	1.6	2.3
PSW	0.0	1.6	2.4
RM	0.0	11.7	11.8
SC	0.0	115.8	228.6
SE	0.0	0.0	12.4
US	2.3	137.3	434.8
Forest Management			
CB	-3.0	-5.6	-5.5
LS	0.8	5.7	14.2
NE	1.9	9.5	23.6
PNWE	0.2	0.2	0.4
PNWW	3.2	9.6	19.1
PSW	0.7	0.8	2.9
RM	1.9	2.0	4.7
SC	70.6	127.7	160.8
SE	28.8	69.2	93.9
US	105.1	219.1	314.2
Agricultural Soil Carbon Sequestration			
CB	39.5	62.2	72.4
GP	20.0	29.3	33.2
LS	33.3	36.9	33.1
NE	6.9	4.7	-3.7
PNWE	1.5	2.4	2.7
PSW	0.3	0.7	0.9
RM	7.5	9.5	9.6
SC	4.5	4.3	-6.0
SE	3.8	7.6	7.0
SW	5.5	10.5	13.2
US	122.7	168.0	162.5

(continued)

Table 4.A.3: Forest and Agricultural GHG Mitigation by Activity, Region, and Price Scenario (continued)

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
Fossil Fuel Mitigation from Crop Production			
CB	6.5	10.5	21.7
GP	1.0	0.8	-0.4
LS	0.4	1.0	1.8
NE	1.1	1.7	1.2
PNWE	0.2	0.2	0.0
PSW	1.3	2.3	3.4
RM	1.2	1.3	1.4
SC	10.2	23.7	33.4
SE	1.3	1.9	5.8
SW	8.7	9.7	9.3
US	31.9	53.1	77.6
Agricultural CH_4 and N_2O Mitigation			
CB	4.1	7.4	24.2
GP	-0.8	-3.3	-8.5
LS	0.1	1.1	1.6
NE	0.9	1.0	1.8
PNWE	0.0	-0.1	-0.6
PSW	0.9	2.7	4.3
RM	4.7	5.2	5.1
SC	-1.1	6.9	21.0
SE	2.5	4.7	9.2
SW	3.9	6.4	8.9
US	15.3	32.0	66.8
Biofuel Offsets			
CB	-0.1	-0.3	51.1
GP	0.3	0.6	1.1
LS	0.1	0.1	19.3
NE	0.0	47.9	125.1
PNWE	0.0	0.0	0.1
PSW	0.0	0.0	0.0
RM	0.0	0.0	0.2
SC	-0.3	-0.4	69.9
SE	0.0	9.2	107.5
SW	0.1	0.1	0.3
US	0.1	57.2	374.6

(continued)

Table 4.A.3: Forest and Agricultural GHG Mitigation by Activity, Region, and Price Scenario (continued)

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
All Activities			
CB	49.0	80.8	326.4
GP	20.5	27.3	25.5
LS	34.6	44.8	84.9
NE	10.9	64.7	148.1
PNWE	2.2	4.3	4.8
PNWW	3.2	9.6	19.1
PSW	3.2	8.0	13.8
RM	15.3	29.8	32.7
SC	83.9	278.1	507.5
SE	36.4	92.6	236.0
SW	18.1	26.7	31.7
US	277.3	666.7	1,430.4

Table 4.A.4: Key Results at the National Level by Activity, Time Period, and Rising Price Scenarios
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for representative years 2015, 2025, and 2055.

Year[a]	Activity	\$20 @ \$1.30/yr	\$3 @ 1.5%/yr	\$3 @ 4%/yr
2015	Afforestation	132	0	7
	Forest management	101	61	62
	Agricultural soil carbon sequestration	105	103	25
	Fossil fuel mitigation from crop production	38	20	21
	Agricultural CH_4 and N_2O mitigation	31	13	14
	Biofuel offsets	4	0	0
	All activities	411	198	129
2025	Afforestation	649	4	11
	Forest management	176	21	–67
	Agricultural soil carbon sequestration	135	116	48
	Fossil fuel mitigation from crop production	47	17	18
	Agricultural CH_4 and N_2O mitigation	59	15	18
	Biofuel offsets	153	0	0
	All activities	1,218	174	28
2055	Afforestation	565	–3	15
	Forest management	423	19	141
	Agricultural soil carbon sequestration	–26	–3	76
	Fossil fuel mitigation from crop production	113	50	62
	Agricultural CH_4 and N_2O mitigation	101	12	25
	Biofuel offsets	1,021	0	352
	All activities	2,196	75	671

[a] Year represents midpoint of decade tracked in FASOMGHG model (e.g., 2015 represents the midpoint of the 2010 to 2019 decade).